

*XLIIèmes Rencontres de Moriond:
QCD and Hadronic Interactions
La Thuile, March 17–24, 2007*

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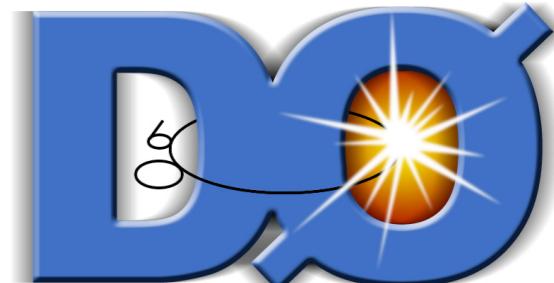
*XLIIèmes Rencontres de Moriond:
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Measurements of Top Properties at the Tevatron



*Ulrich Husemann
Yale University
on behalf of the
CDF and DØ Collaborations*

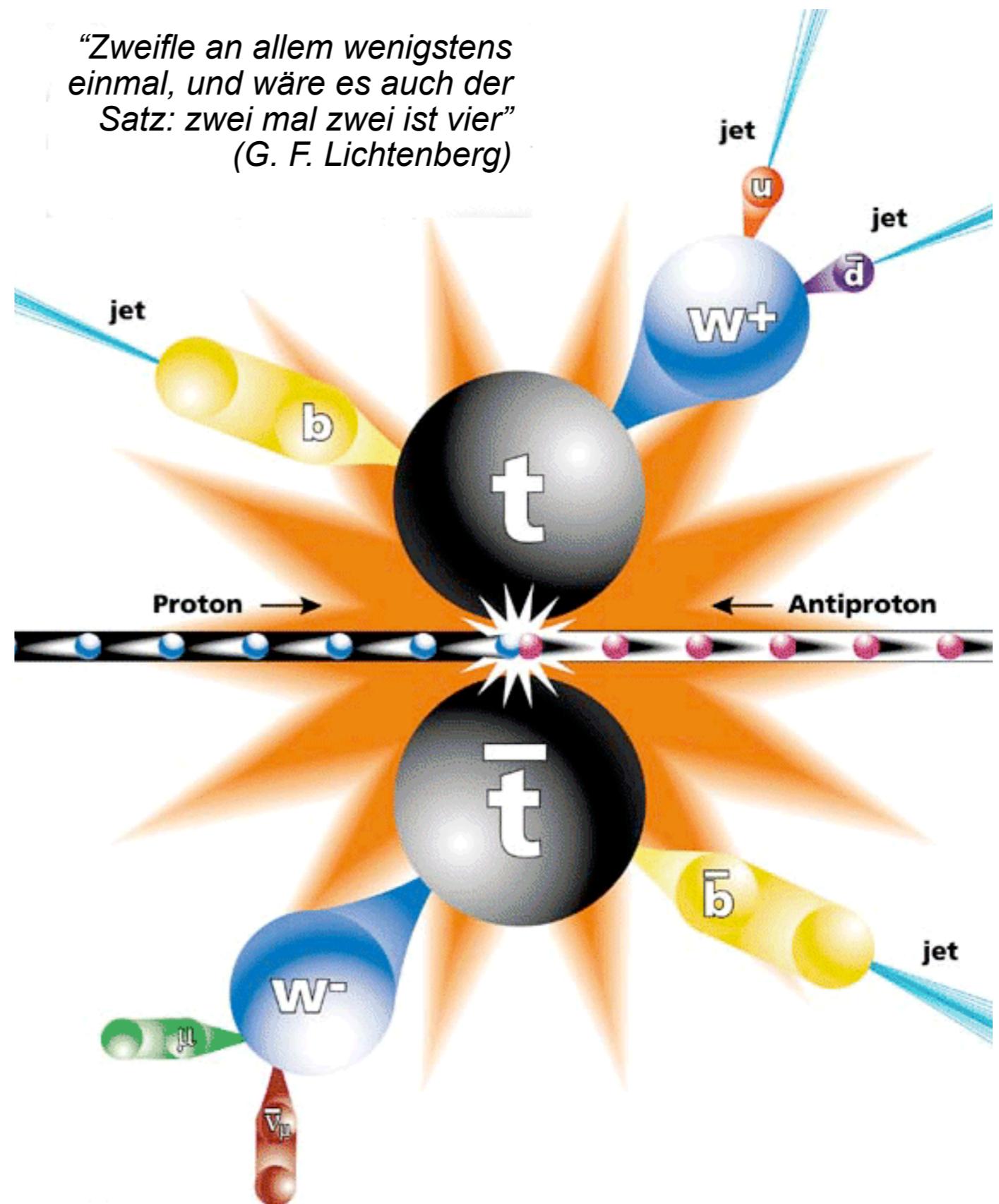


Measuring Top Properties

- Top plays a **special role** in the Standard Model (SM):
 - Mass close to scale of electroweak symmetry breaking
 - Top is the only “free” quark: lifetime < hadronization time
- From Top discovery in 1995 to **precision physics** in 2007:
 - Datasets: 1000s of Top events
 - Mass & cross section precisely measured
 - Evidence for single Top
 - Measurements of Top properties try to answer:

Is the Top really the Standard Model Top?

“Zweifle an allem wenigstens einmal, und wäre es auch der Satz: zwei mal zwei ist vier”
(G. F. Lichtenberg)

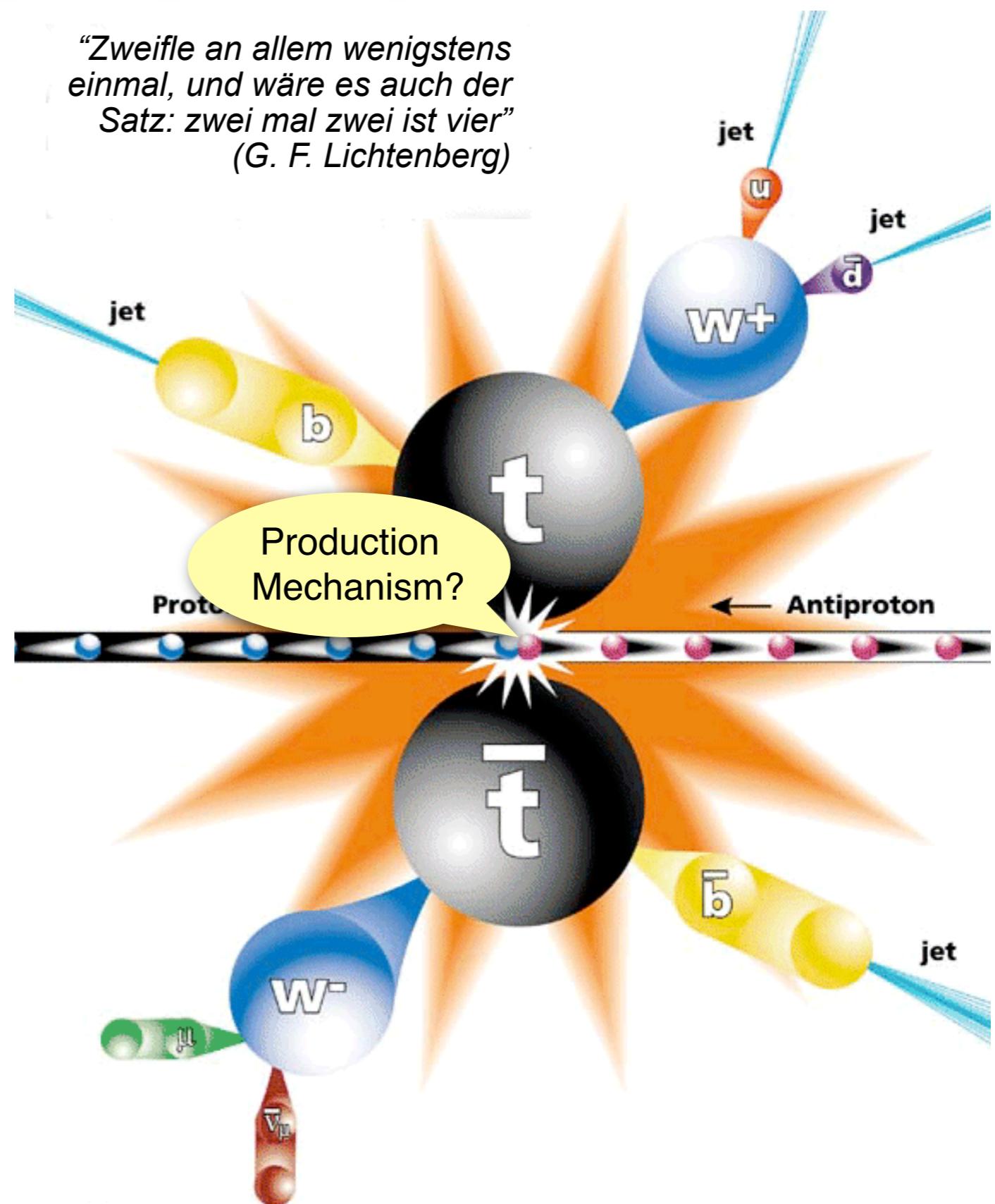


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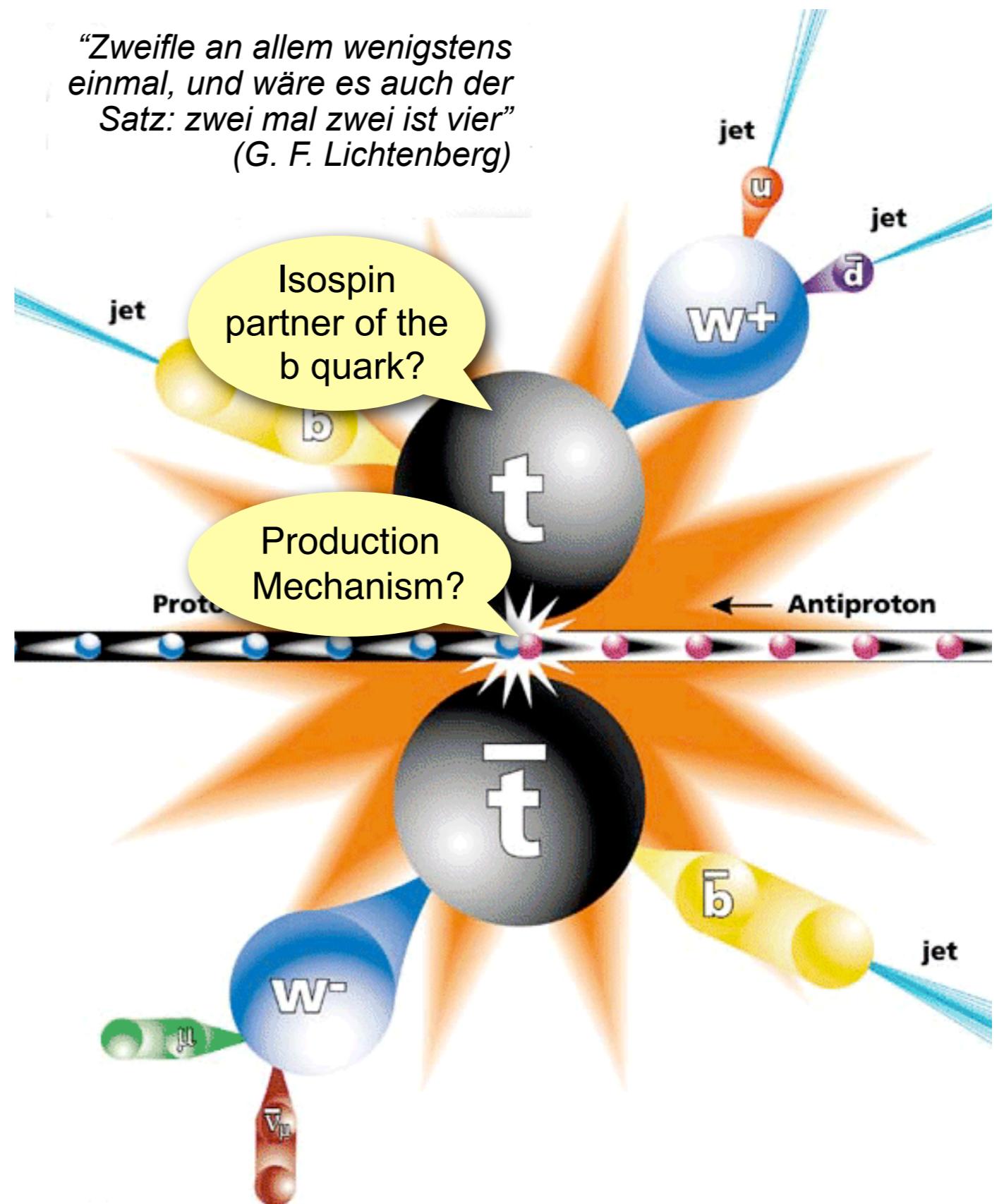


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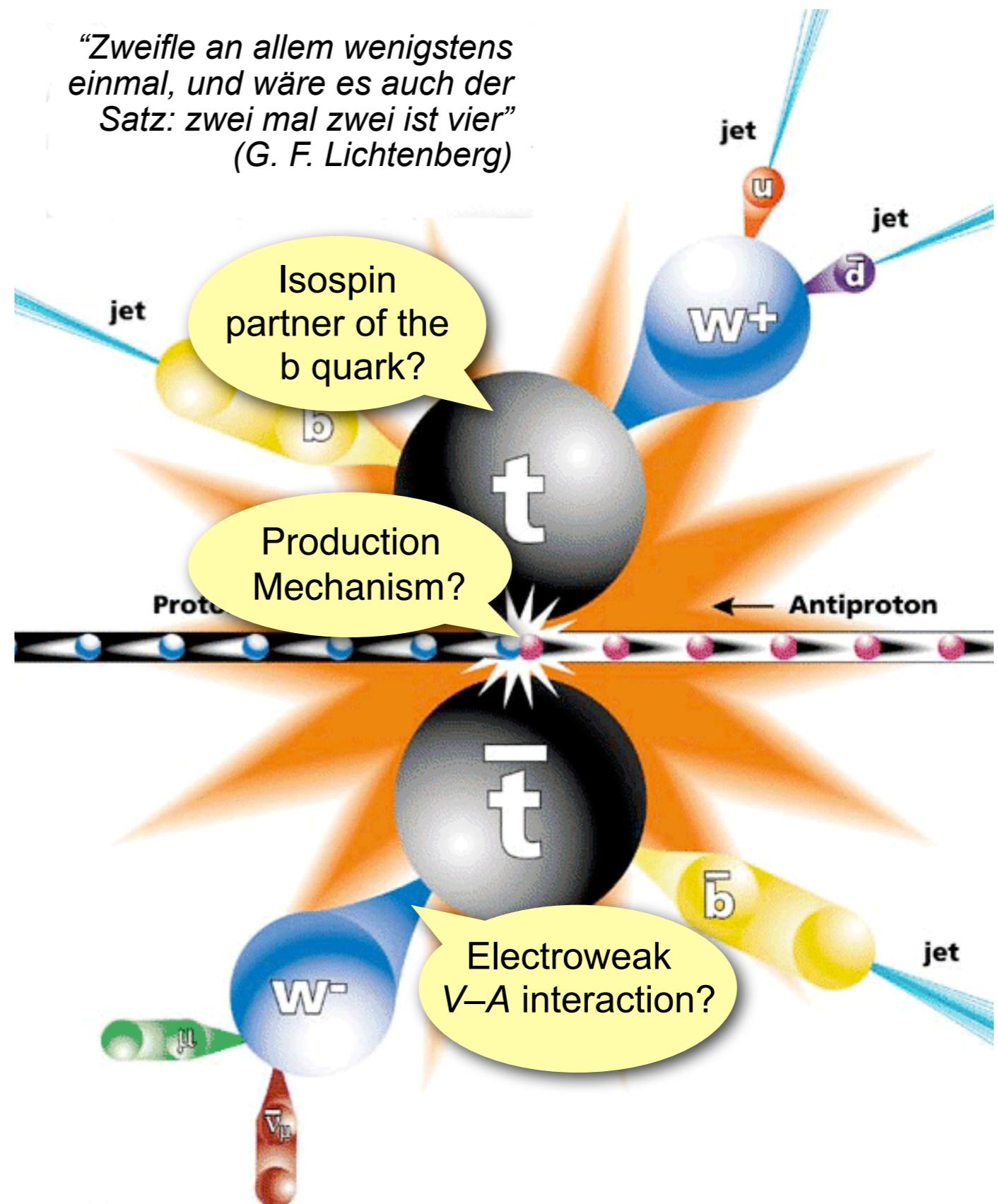
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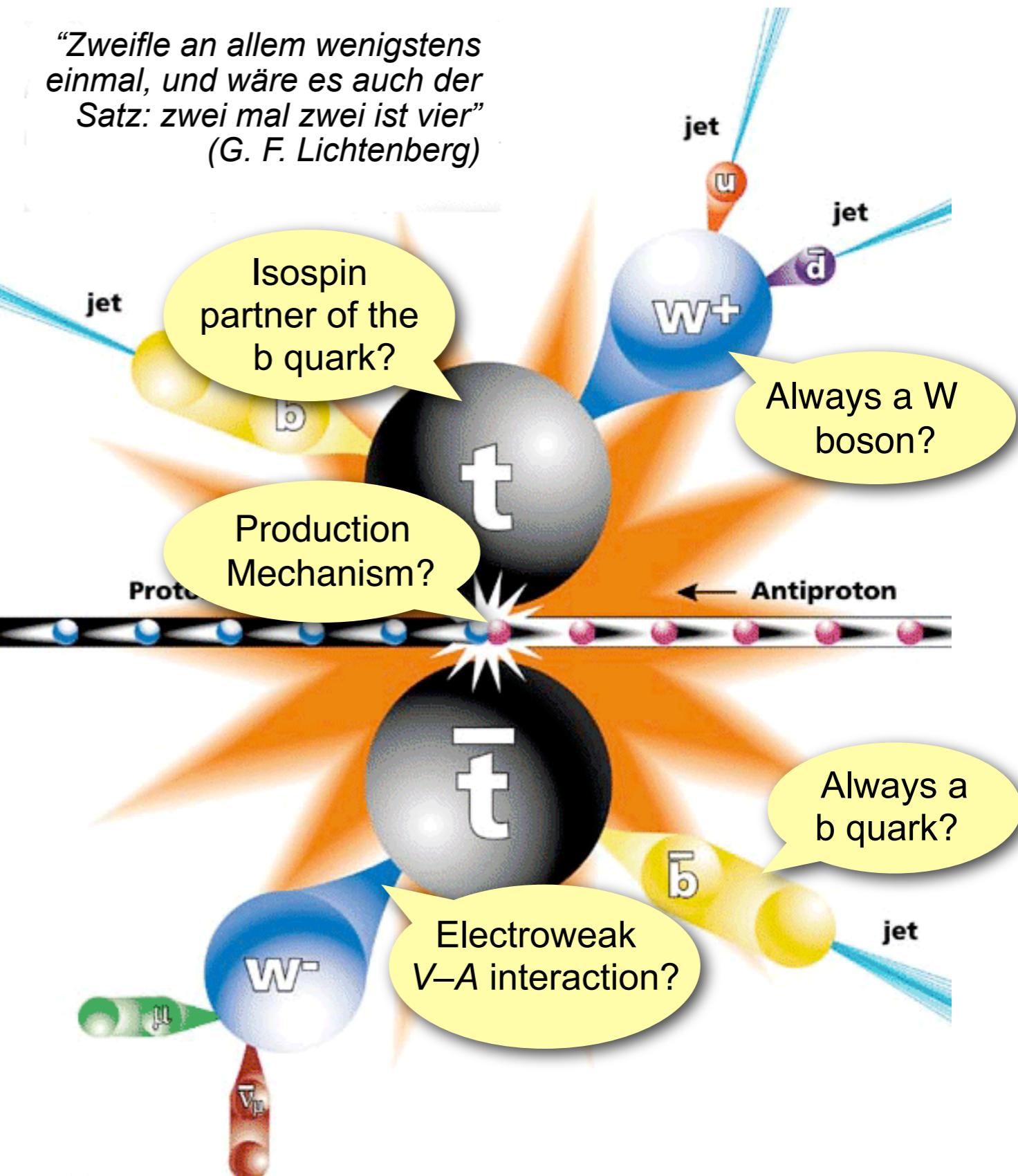
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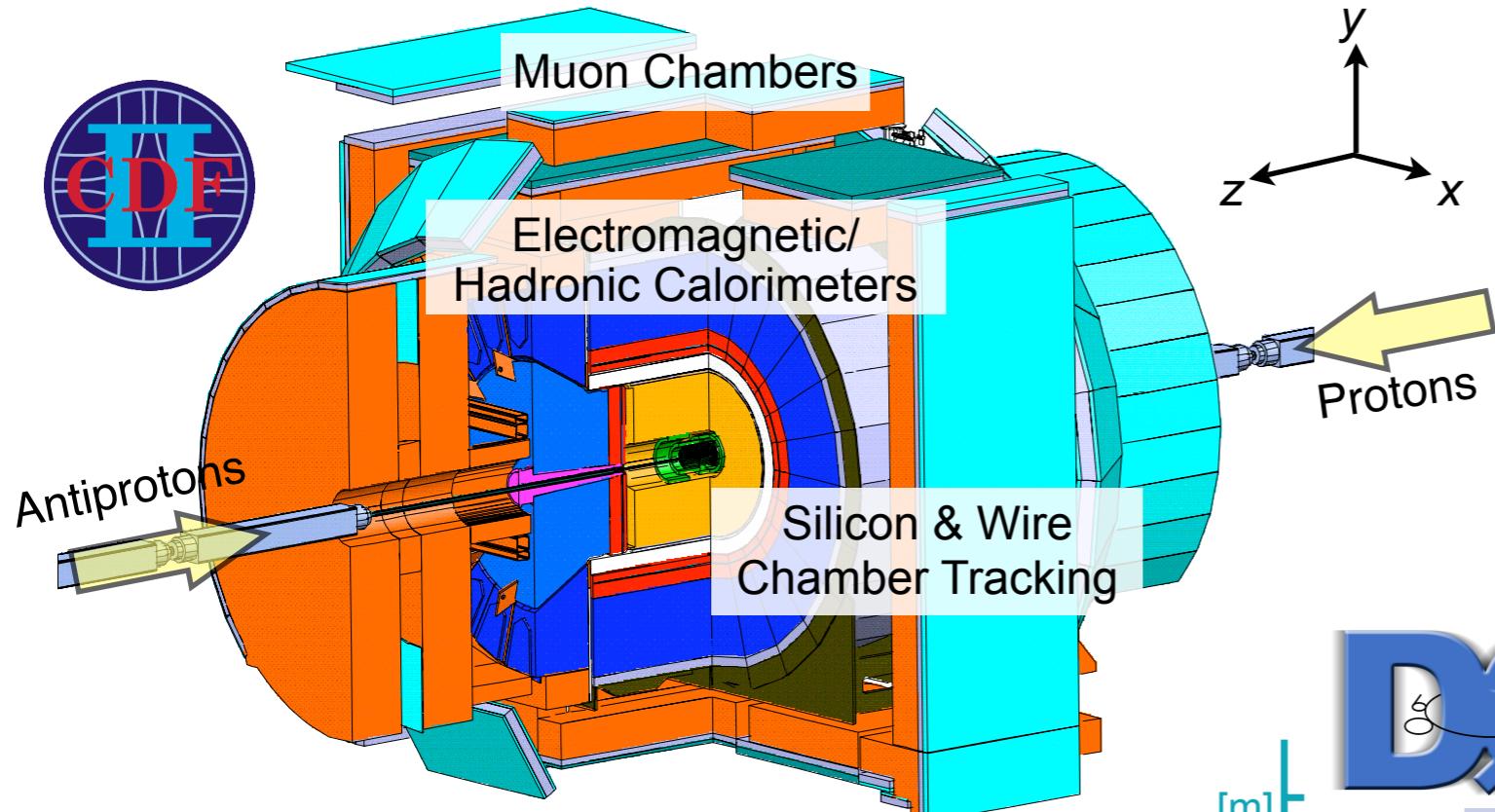
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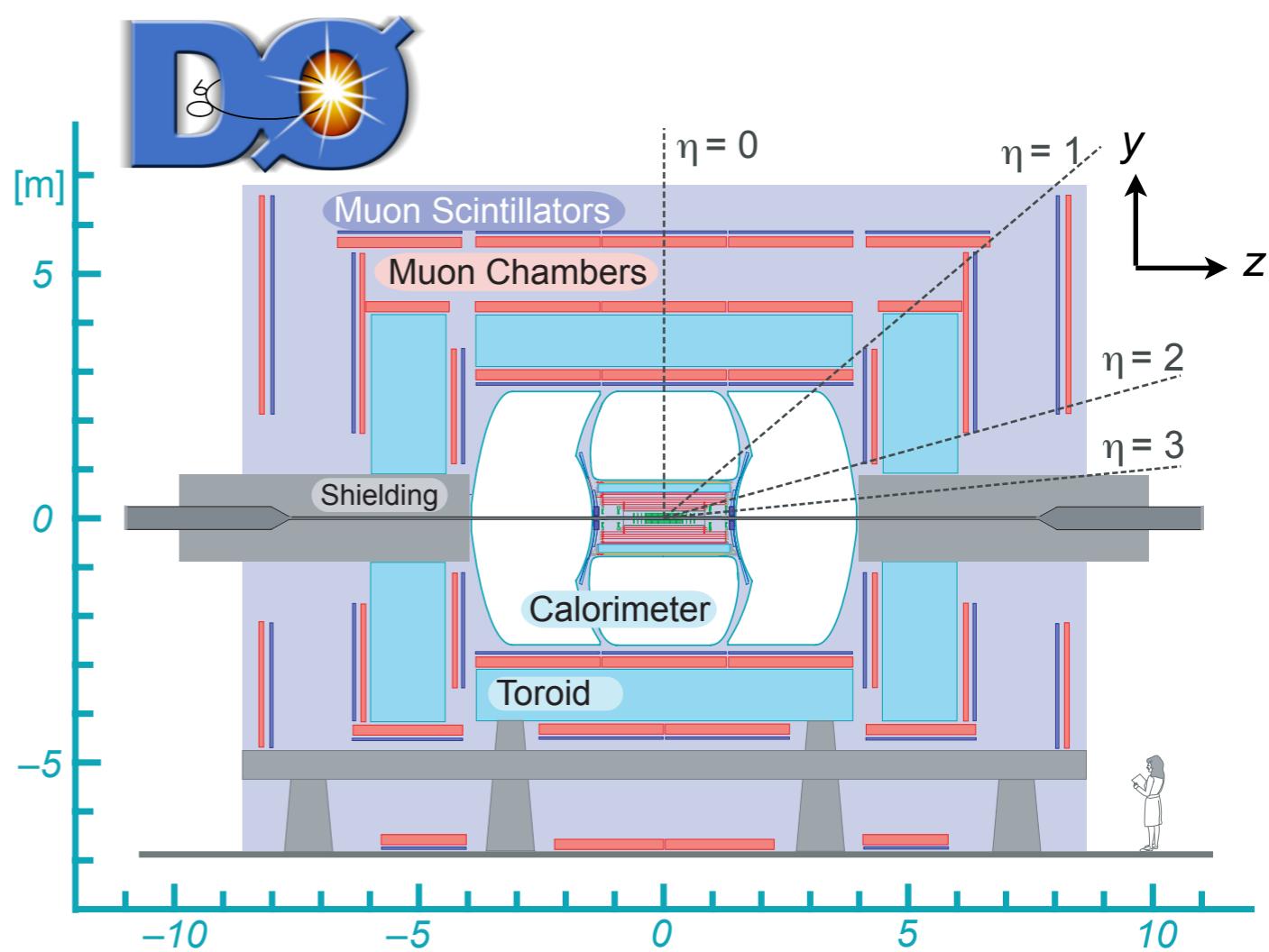
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The Tevatron: CDF & DØ



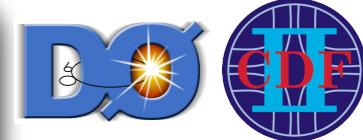
- Tevatron Run II (2001–2009):
 - Proton-antiproton collider: $\sqrt{s} = 1.96 \text{ TeV}$
 - Two multi-purpose experiments: CDF & DØ
 - More than 2 fb^{-1} of integrated luminosity recorded per experiment
 - Expect $6\text{--}8 \text{ fb}^{-1}$ by end of Run II

Results presented here use between 230 pb^{-1} and 1.0 fb^{-1} of data (expect 2.0 fb^{-1} results by this summer)

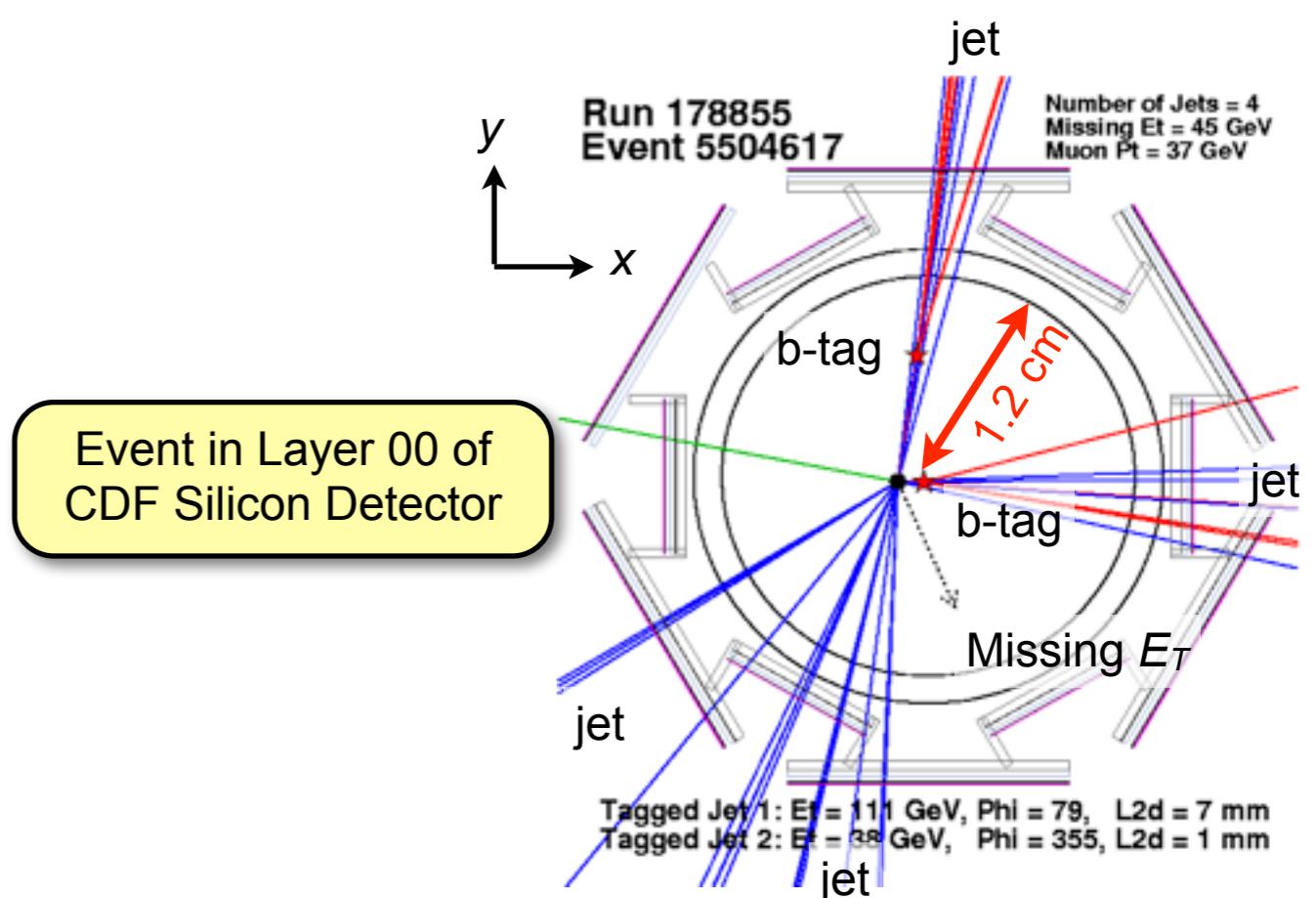
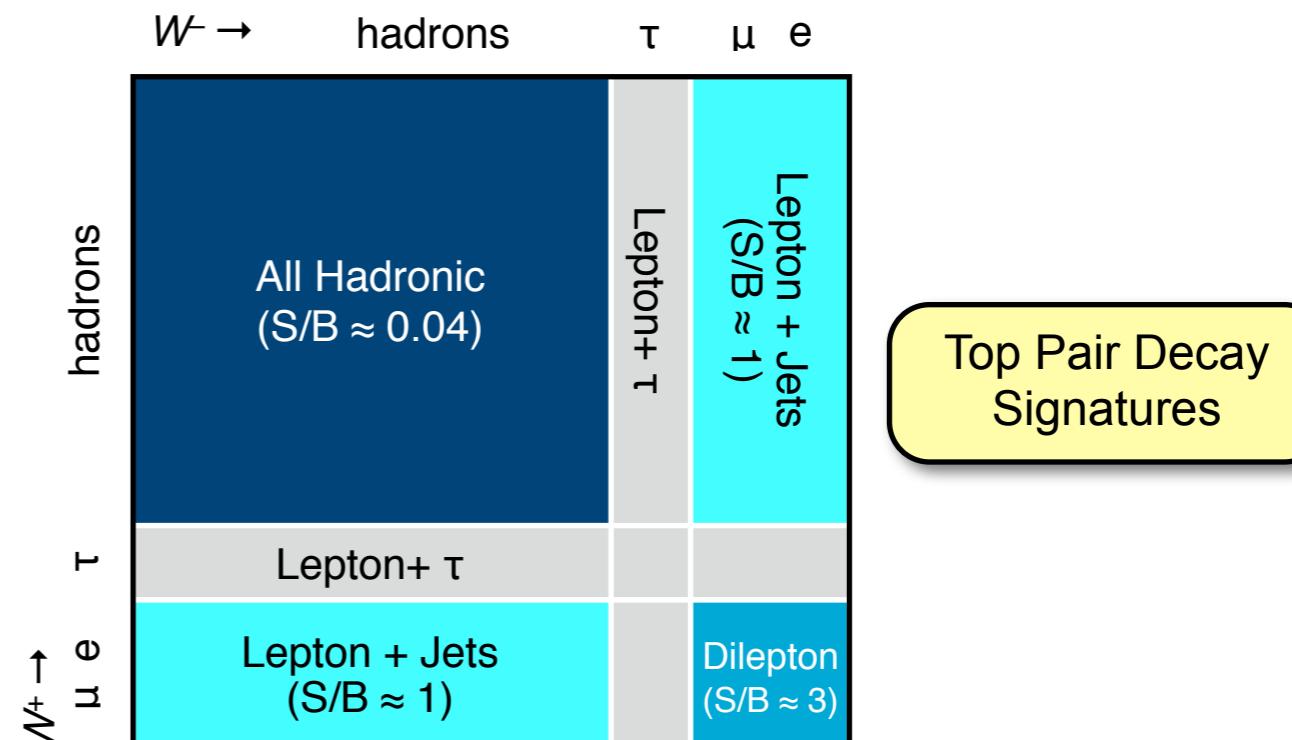




Top Analysis Basics



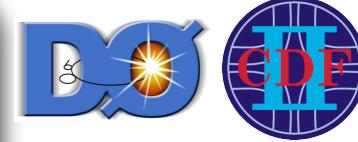
- Top decay in the Standard Model:
 $t \rightarrow W b$ (BR $\approx 100\%$)
 - $t\bar{t}$ decay signatures characterized by W decays, in this talk mainly:
 - Lepton+Jets (30% of all decays)
 - Dilepton (5% of all decays)
 - Backgrounds and systematic uncertainties: built on experience gained in Top mass and cross section analyses
 - Main background: W + Jets
 - Main systematic uncertainty: jet energy scale
 - Important tool: b-tagging
 - Top events: two jets from b quarks
 - Identify B hadrons by displaced secondary vertex



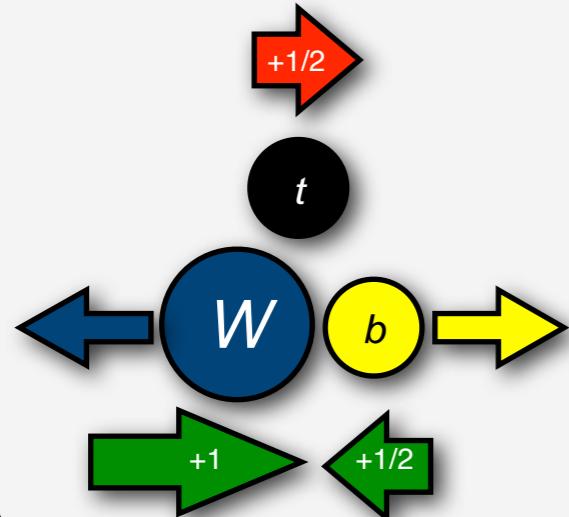


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W Helicity in Top Decays

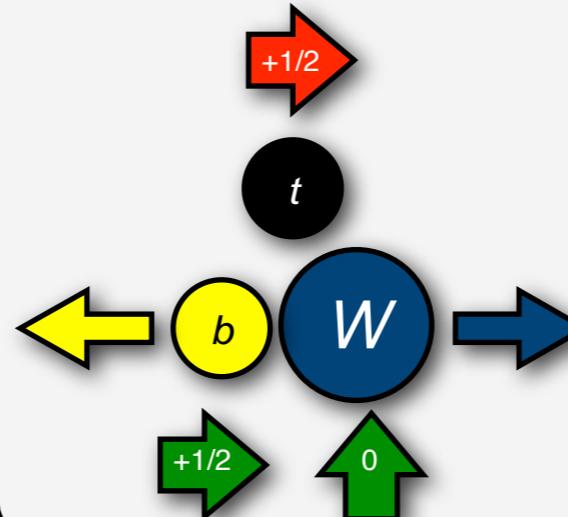


Left-handed Fraction f^-



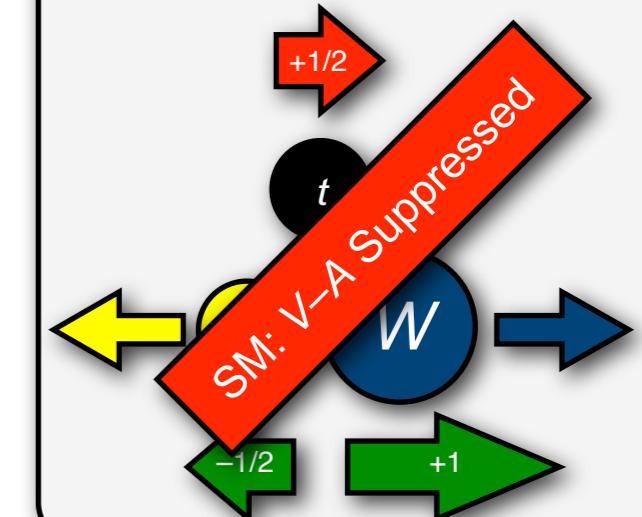
SM Prediction: 0.3

Longitudinal Fraction f^0



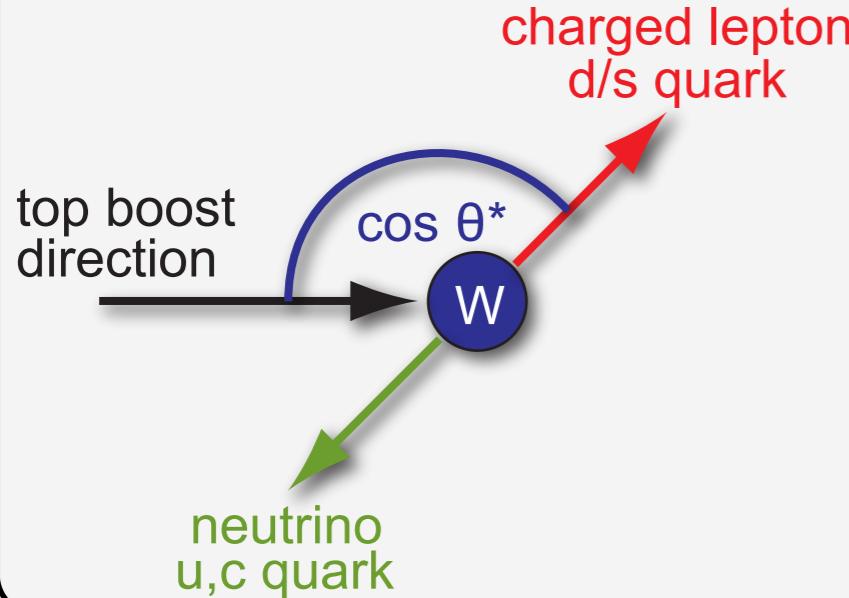
SM Prediction: 0.7

Right-handed Fraction f^+



SM Prediction: 0.0

Definition of $\cos \theta^*$



- Test **V–A structure** of $t \rightarrow Wb$ decay vertex
 - Close to scale of electroweak symmetry breaking
 - Electroweak interactions couple to left-handed quarks
 $\rightarrow V+A$ component: New Physics
- Observable “ $\cos \theta^*$ ”:
 - Decay angle of down-type particle from W decay w.r.t. Top boost direction in W rest frame
 - Reconstructed from kinematic fitter or invariant mass of lepton and b-jet (“ M_{lb} ”)



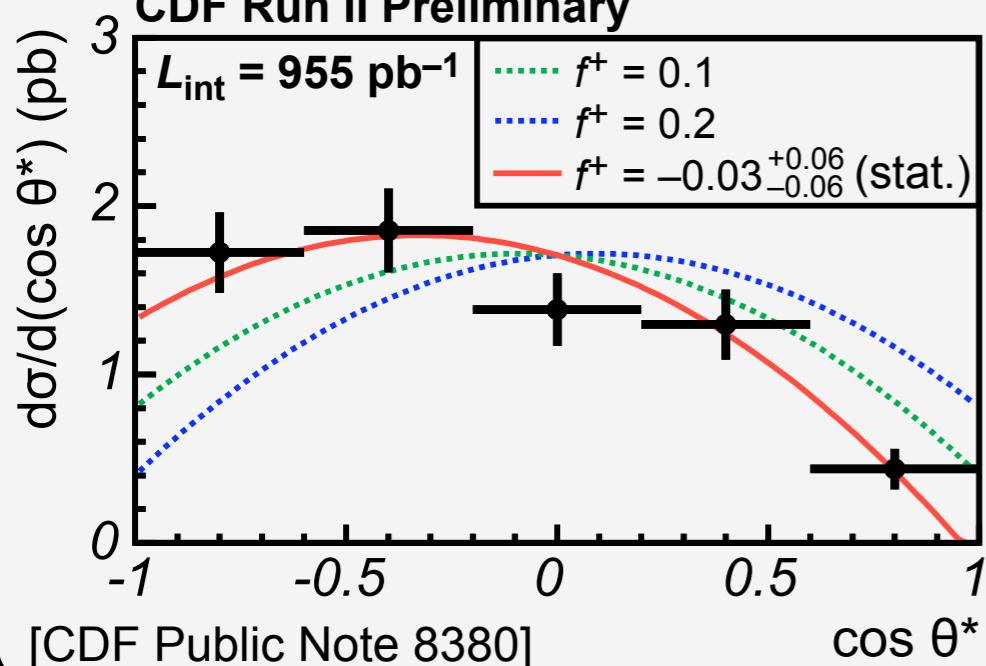
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W Helicity: Results



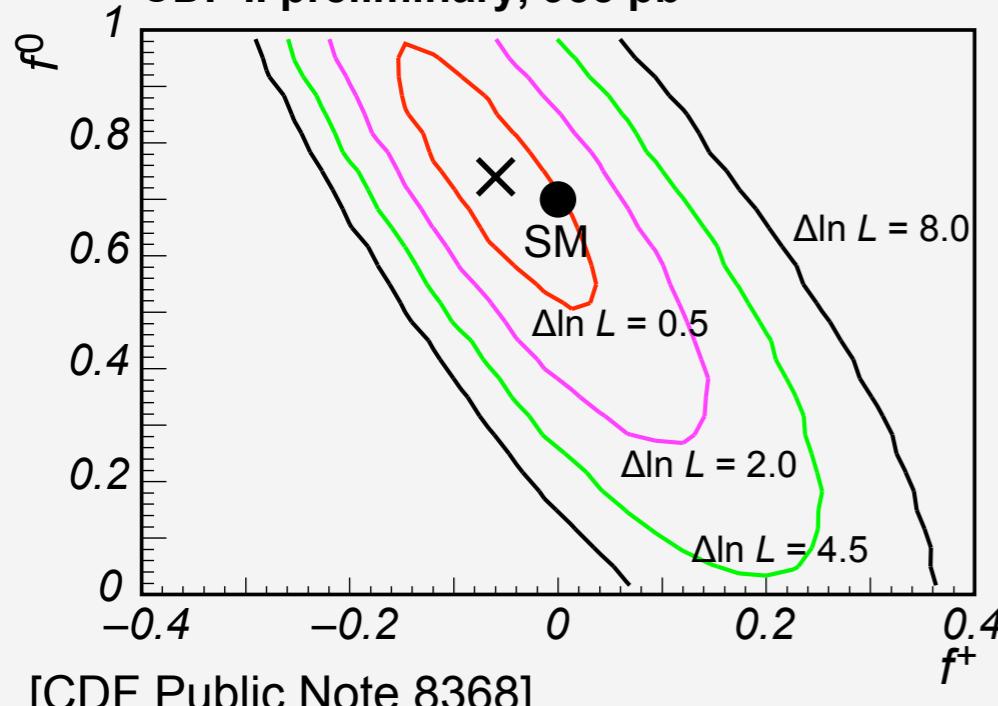
Unfolded Differential Cross Section

CDF Run II Preliminary



2D Fit to f^0 and f^+ : Likelihood Contours

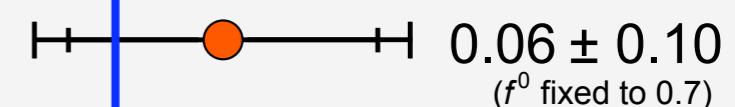
CDF II preliminary, 955 pb^{-1}



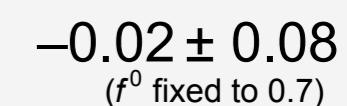
W Helicity Summary

(Spring 2007)

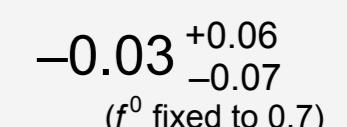
L+J & Dilepton: DØ
(370 pb^{-1} , PRD **75** 031102)



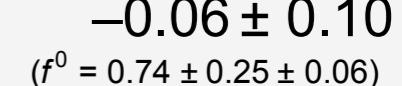
L+J & Dilepton: CDF
(750 pb^{-1} , PRL **98** 072001)



Lepton+Jets: CDF
(955 pb^{-1} , prel.)



L+J 2D: CDF
(955 pb^{-1} , prel.)



right-handed fraction f^+

- 4 independent analyses with Lepton+Jets and Dilepton data samples, up to 1 fb^{-1} of data
- Analyses **statistics-limited**
- All results **consistent with Standard Model**



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Top Charge: 2/3e or -4/3e?



New

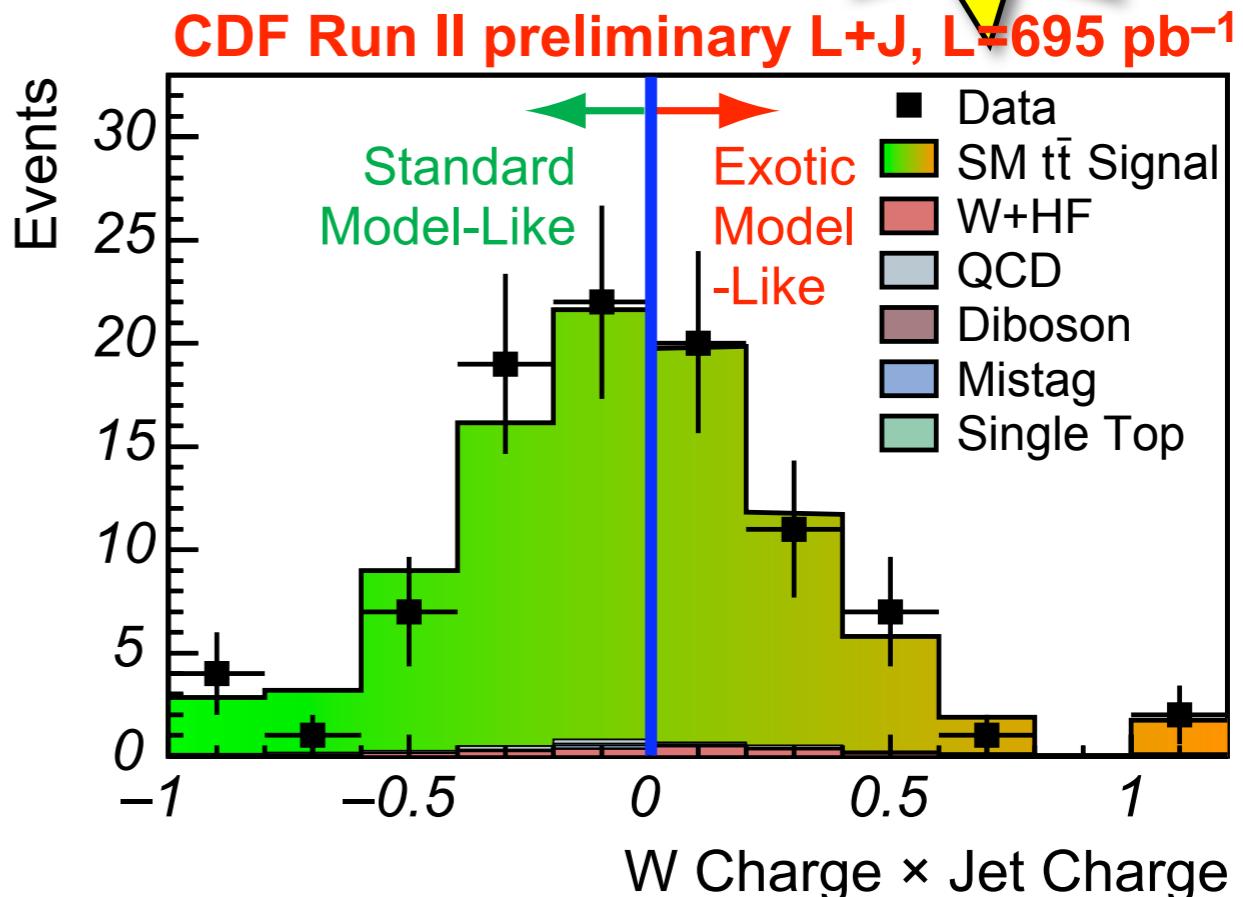
- From fits to electroweak data: observed “Top” could be **exotic quark with charge $-4/3e$** , true Top mass: 258 GeV/c²

[D. Chang *et al.*, Phys. Rev. D59 (1999) 091503]

- Direct measurement:
 - Measure **W charge**: lepton charge
 - Correct **pairing** of W and b jet
 - Flavor of b-quark**: “Jet Charge” (calibrated with dijet data)

$$\text{JetQ} = \frac{\sum_{\text{tracks}} (\vec{p}_{\text{track}} \cdot \vec{p}_{\text{jet}})^{0.5} \cdot Q_{\text{track}}}{\sum_{\text{tracks}} (\vec{p}_{\text{track}} \cdot \vec{p}_{\text{jet}})^{0.5}}$$

- Counting experiment:
 - Lepton+Jets & Dilepton
 - 62 Standard Model-like events
 - 48 exotic model-like events



Statistical Treatment: Hypothesis Test

- Null hypothesis: SM is correct
- Decide *a priori*: probability of incorrectly rejecting SM: $\alpha = 0.01$
- If exotic model is true: 81% of all p-values are below 0.01
- Measured p-value: 0.35, larger than α
 - data consistent with SM
 - **exotic model excluded at 81% C.L.**

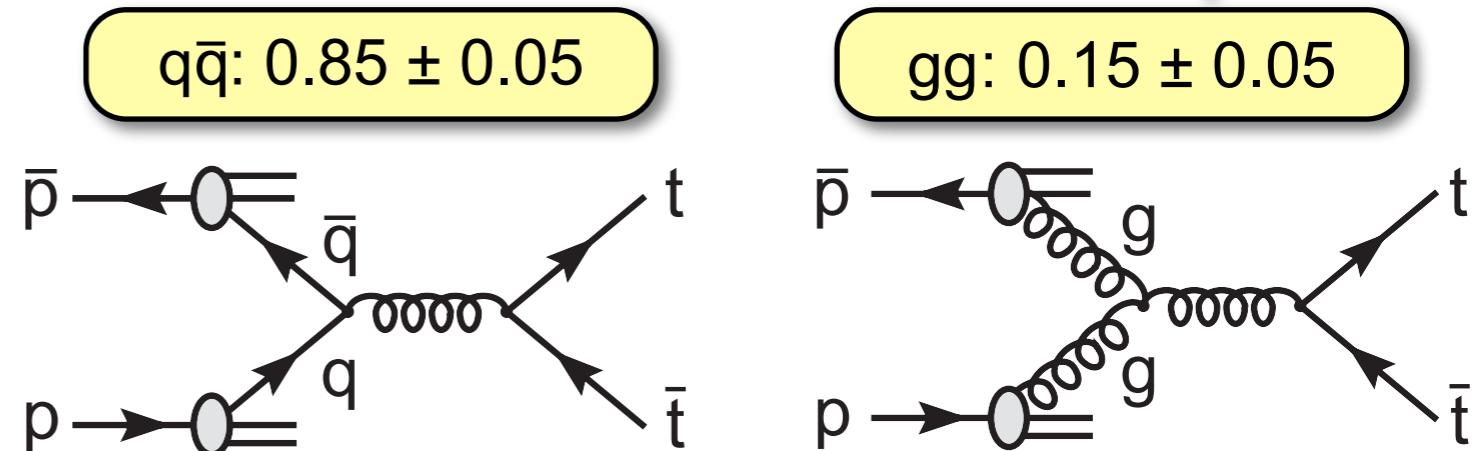


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Top Production Mechanism



- Top pair production at the Tevatron: rather large theoretical uncertainties
- Measurement of **gg fraction** in top production: two very promising approaches, both **statistics-limited**





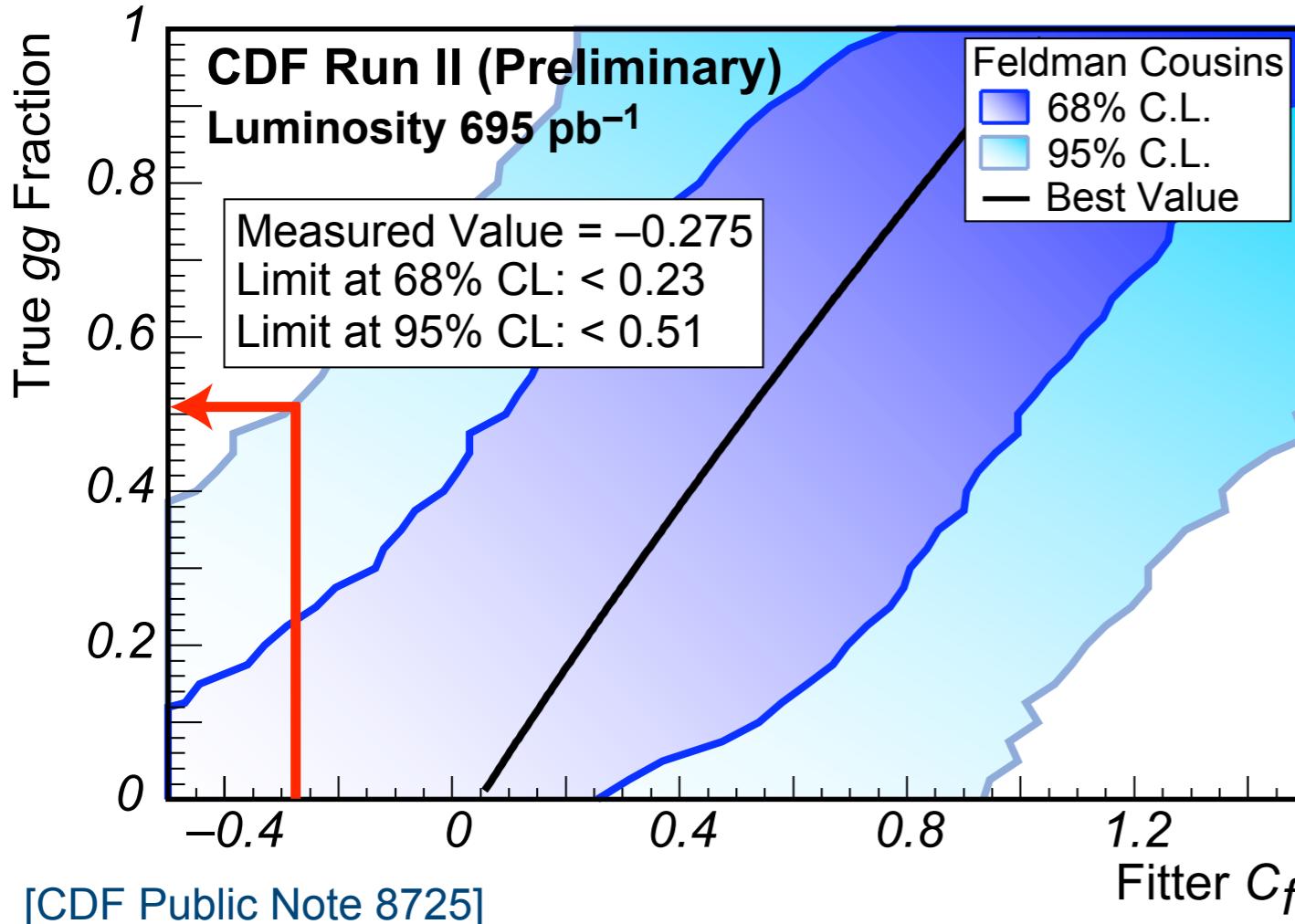
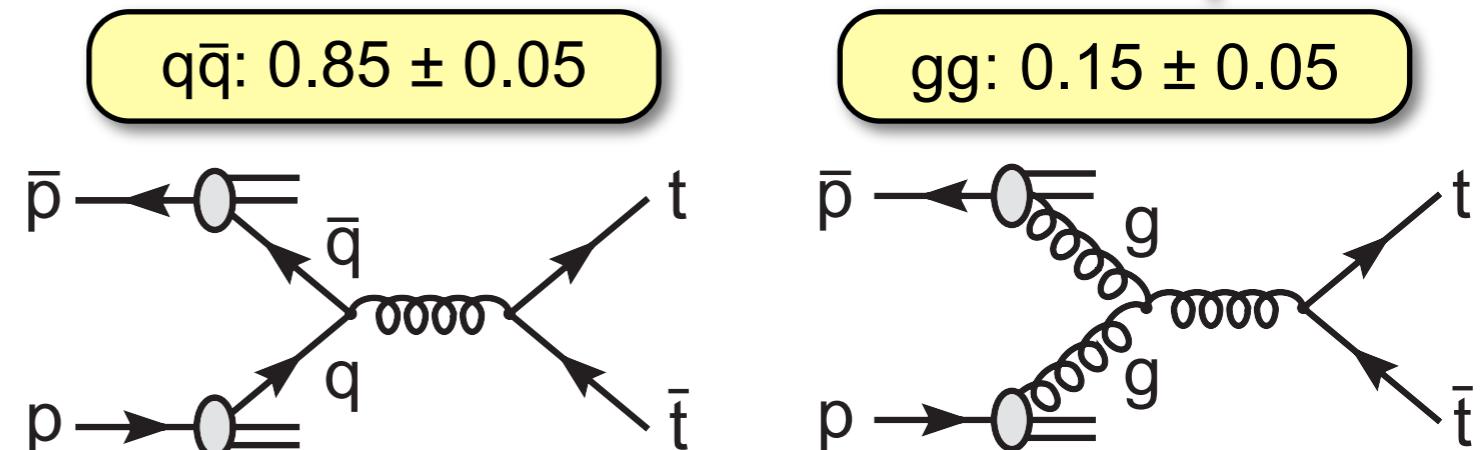
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Approach 1: Neural Network

- Train **neural network** on production and decay kinematics
- Distinguish $q\bar{q} \rightarrow t\bar{t}$, $gg \rightarrow t\bar{t}$, and background from $W + \text{Jets}$
- Neural network input: velocity and angle of Top, decay angles
- Derive Feldman-Cousins limit for gg fraction

$$\frac{\sigma(gg \rightarrow t\bar{t})}{\sigma(pp \rightarrow t\bar{t})} < 0.51 \quad (95\% \text{ C.L.})$$



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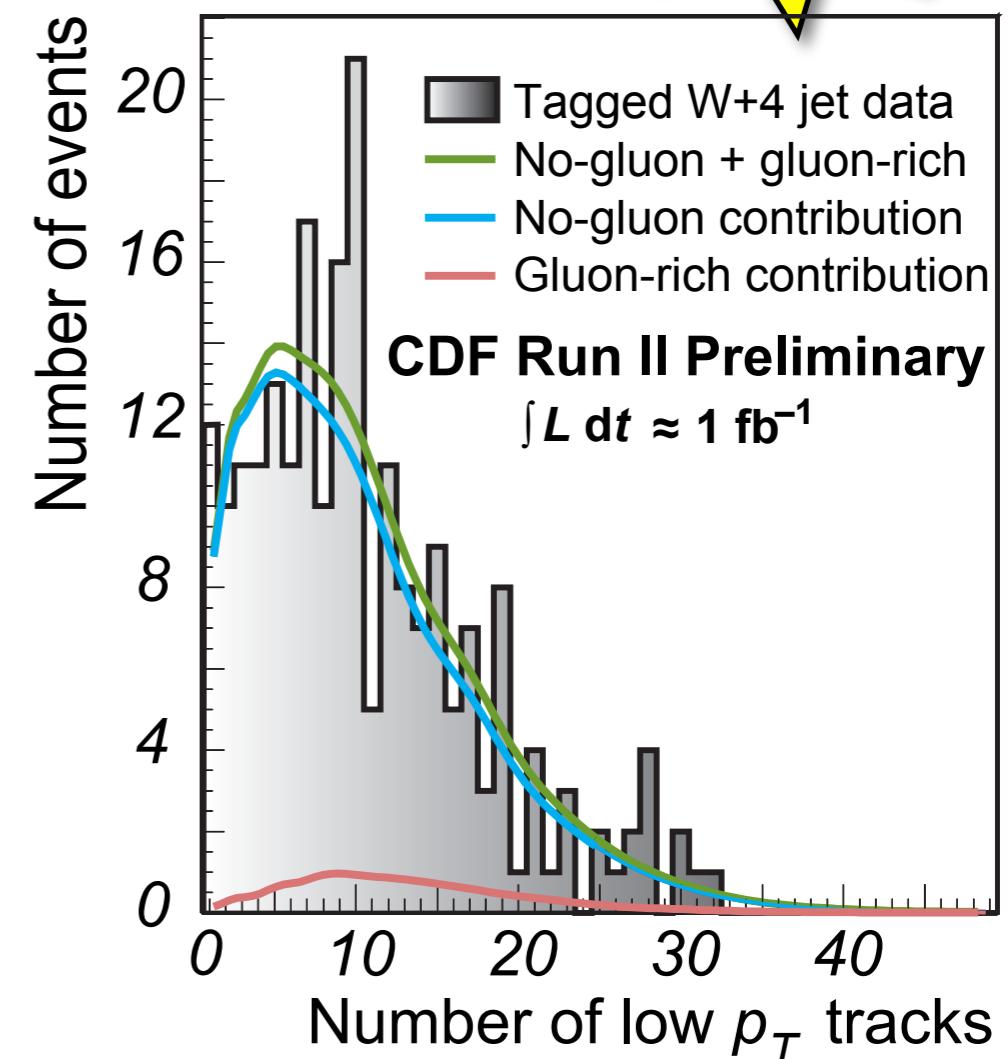
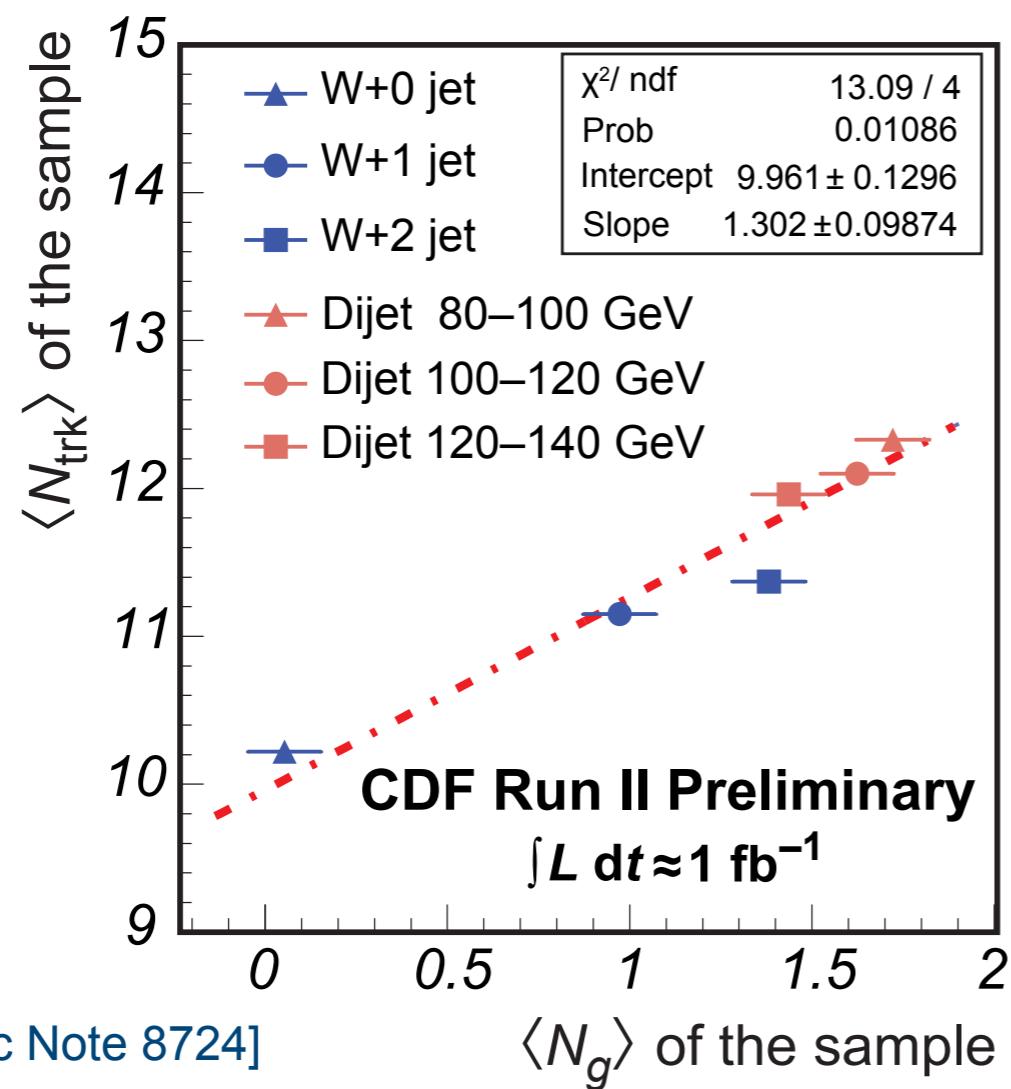
Top Production Mechanism



New

Approach 2: Track Multiplicity

- Average multiplicity of low- p_T tracks strongly correlated with average number of gluons
- Calibrate gluon content with data:
 - $W + 0$ Jets sample: approx. gluon-free
 - Low energy dijet sample: gluon rich



- Extrapolate to Top-rich $W + 4$ Jets sample, create templates for track multiplicity
- Fit templates to data:

$$\frac{\sigma(gg \rightarrow t\bar{t})}{\sigma(p\bar{p} \rightarrow t\bar{t})} = 0.01 \pm 0.16 \text{ (stat.)} \pm 0.07 \text{ (syst.)}$$



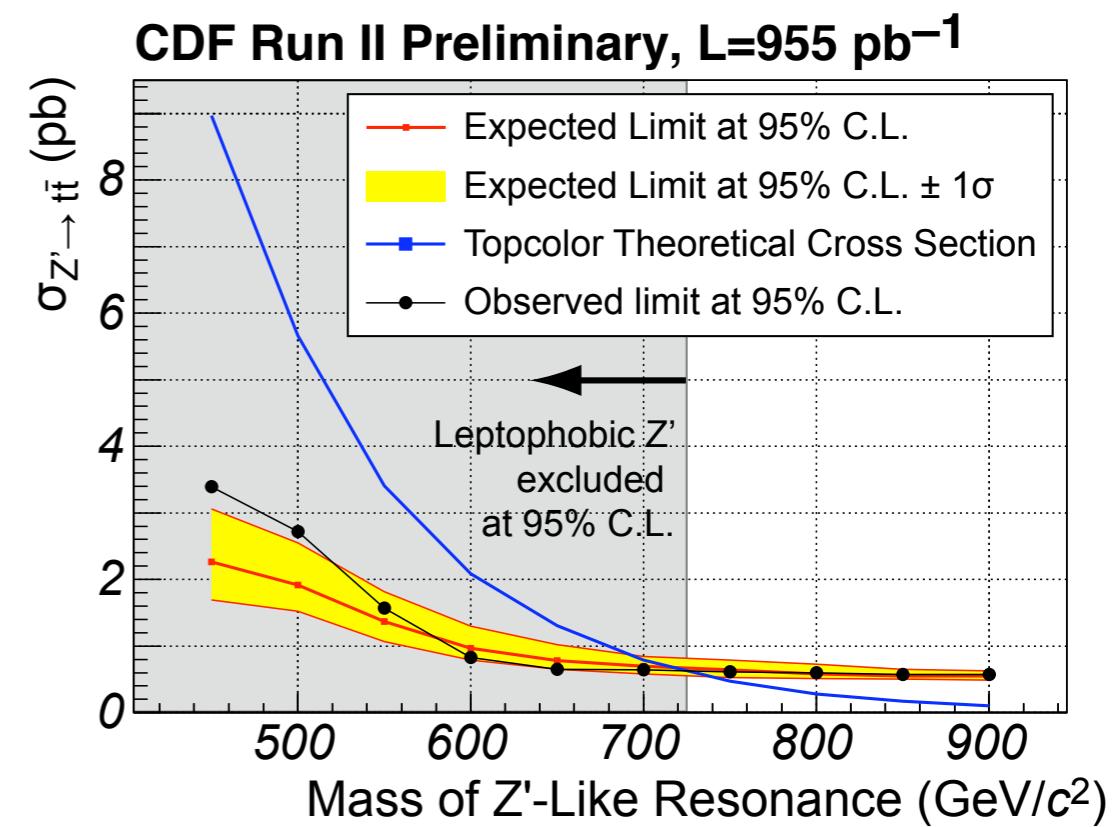
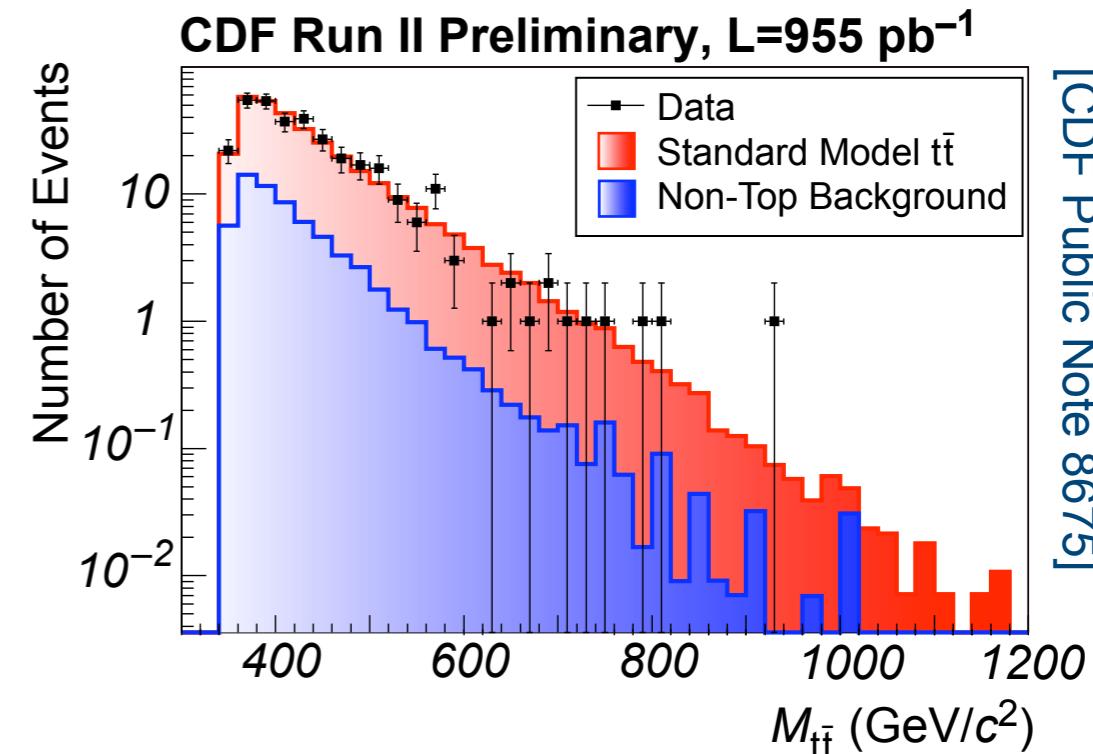
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Search for $t\bar{t}$ Resonances

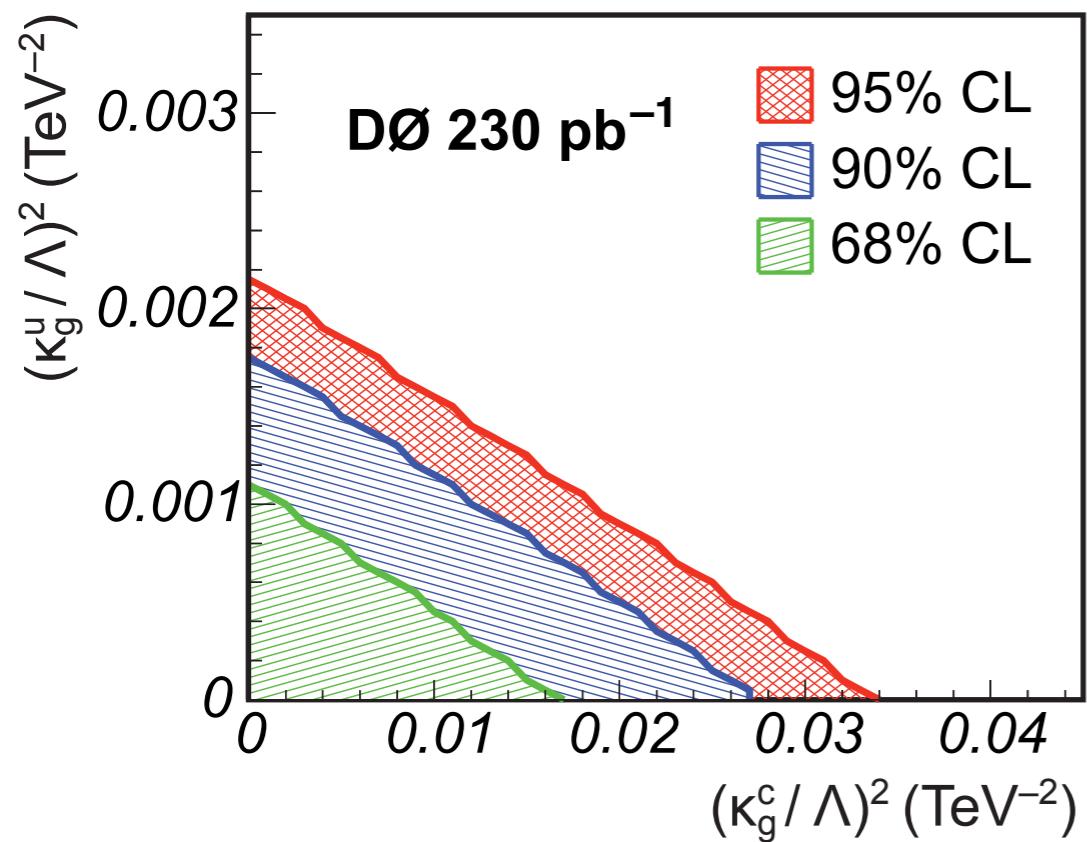
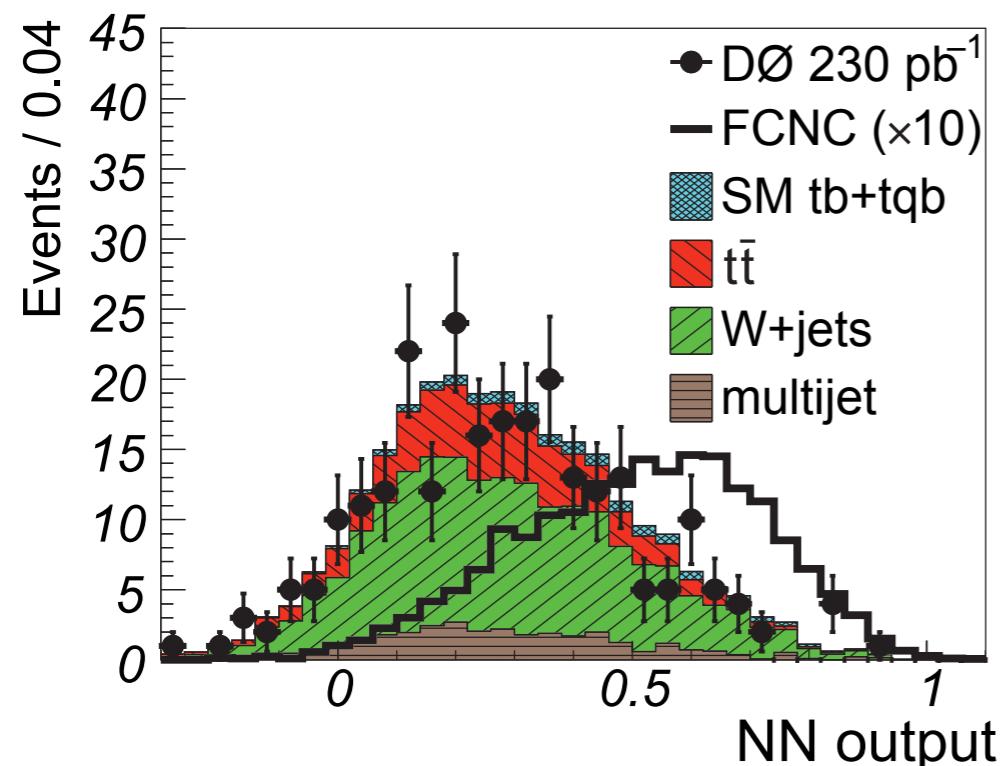


- Top pairs could be produced by **heavy particle decays**: $X \rightarrow t\bar{t}$
- E.g.: Topcolor-Assisted Technicolor
 - $X = Z'$ couples strongly to 3rd generation, weakly to 1st and 2nd generation
 - Z' does not couple to leptons (“leptophobic”)
 - Assume narrow resonance: $\Gamma_Z = 0.012 M_Z$
- Experimental challenge:
 - Reconstruct invariant $t\bar{t}$ mass with kinematic fitter (or matrix-element methods)
 - Understand background composition and kinematics
 - Limit on production of leptophobic Z' :

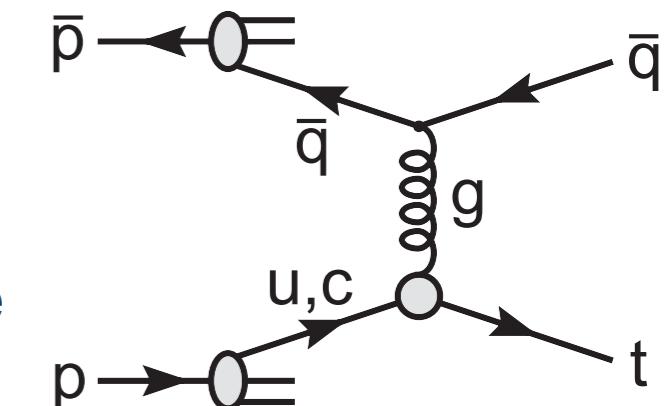
$M_{Z'} > 725 \text{ GeV}/c^2$ (95% C.L.)



Single Top via FCNC



- Flavor changing neutral currents (FCNC) in the Top sector:
 - Heavily suppressed in the Standard Model, e.g. $BR(t \rightarrow cg) \approx 5 \times 10^{-12}$
 - Any signal at the Tevatron: **New Physics**
- Study **single Top production via FCNC**:
 - More sensitive than decays
 - Neural network (NN) to discriminate signal/background
- World's new best limit** on $t\text{-}c\text{-}g$ and $t\text{-}u\text{-}g$ couplings $(\kappa/\Lambda)^2 \rightarrow$ previous limits improved by order of magnitude



$$(\kappa_g^c / \Lambda)^2 < 0.023 \text{ TeV}^{-2} \quad (95\% \text{ C.L.})$$

$$(\kappa_g^u / \Lambda)^2 < 0.0014 \text{ TeV}^{-2} \quad (95\% \text{ C.L.})$$

[V. M. Abazov *et al.*, hep-ex/0702005, submitted to PRL]



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Summary & Conclusions



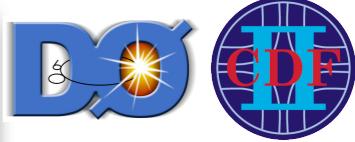
- Tevatron is the **only place** to study Top quarks until LHC turn-on
- Ideal training ground to test new ideas for Top analysis at the LHC
- Study of Top properties is an **exciting and active field** at the Tevatron:
 - New or updated results: W helicity, Top charge, Top production mechanism, anomalous couplings
 - Many results statistics-limited
 - And there is **more**: Top lifetime, search for massive t' quarks, $|V_{tb}|$, ...
- Data **consistent with Standard Model**

Please visit the CDF and DØ public Top web pages for more information:

 - CDF: <http://www-cdf.fnal.gov/physics/new/top/top.html>
 - DØ: http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html



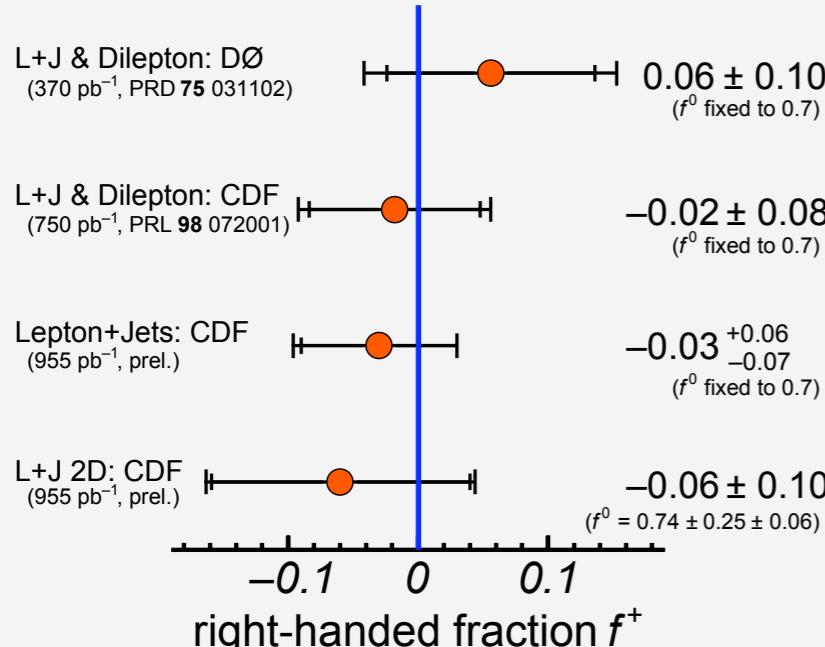
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Backup Slides

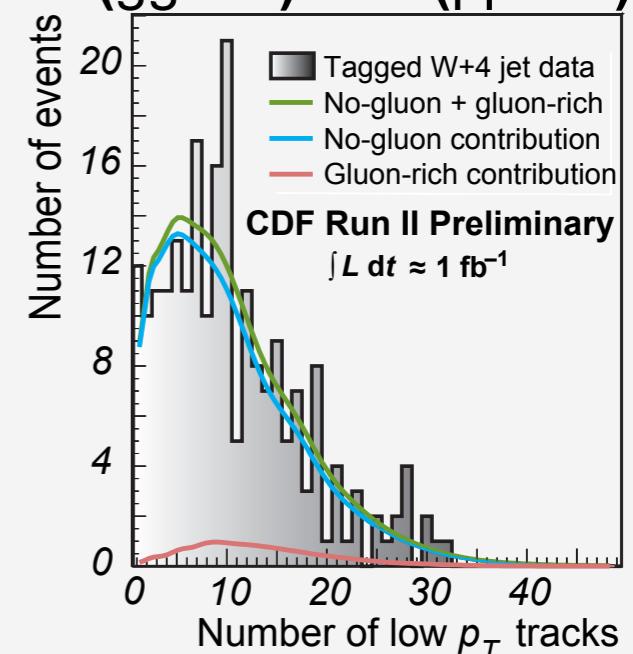
Measurements of Top Properties at the Tevatron

W Helicity: $t \rightarrow W b$ Decay Shows SM V-A Structure

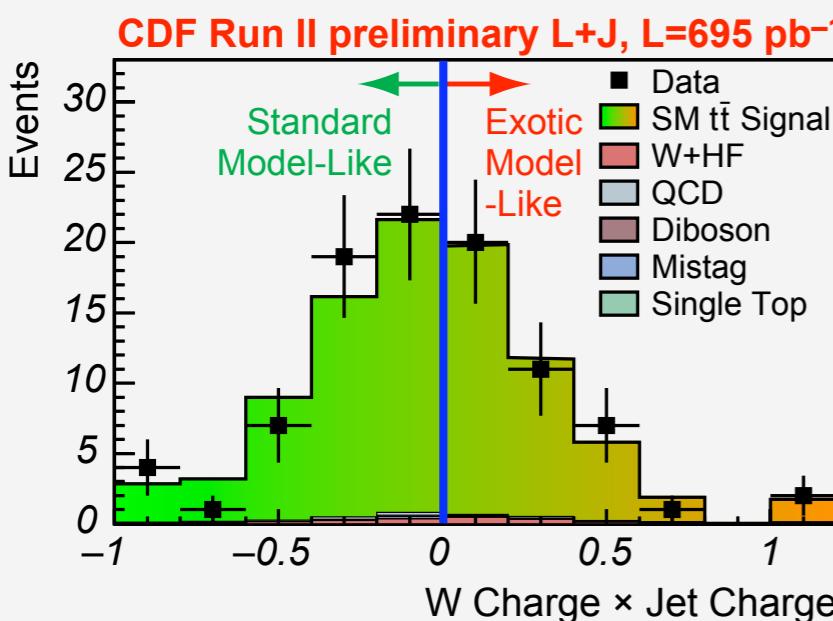


Is the Top really the Standard Model Top?

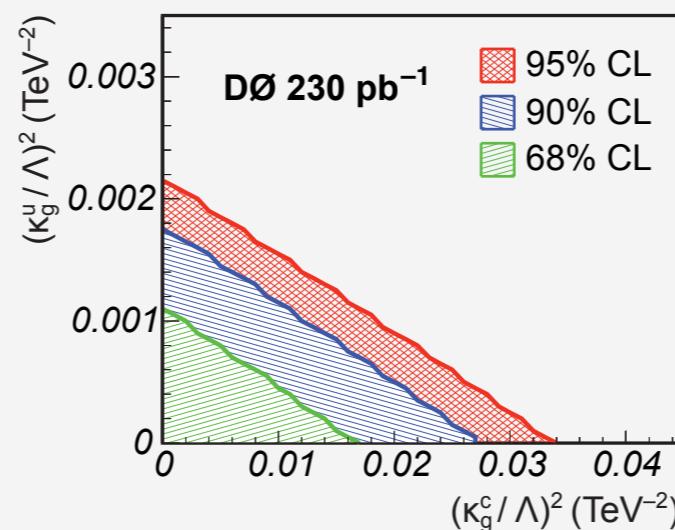
First Measurements of $\text{BR}(gg \rightarrow t\bar{t}) / \text{BR}(pp \rightarrow t\bar{t})$



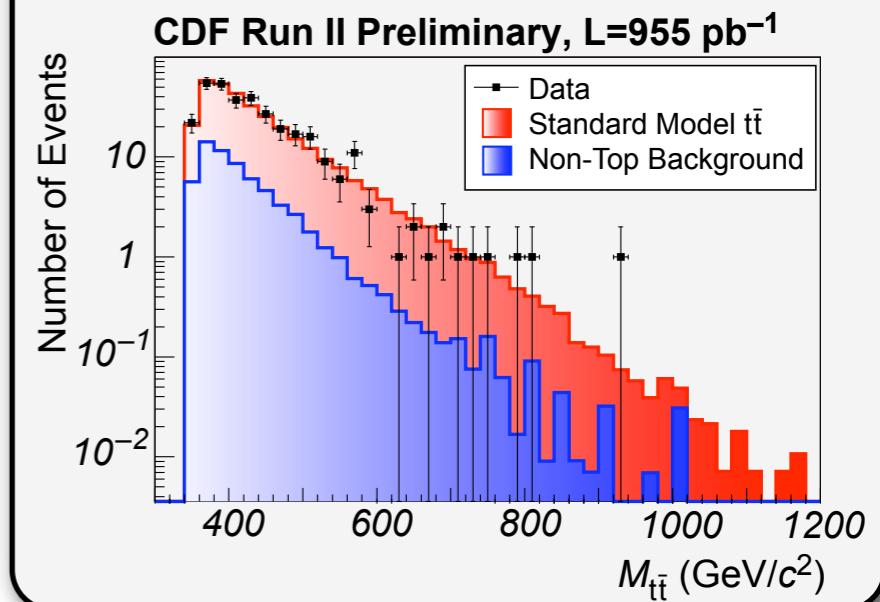
Top Charge: Standard Model Value $2/3e$ Favored



Single Top FCNC: New Limits on Anomalous Top Couplings



$t\bar{t}$ Resonance Production: Leptonphobic Z' excluded up to 725 GeV (95% C.L.)



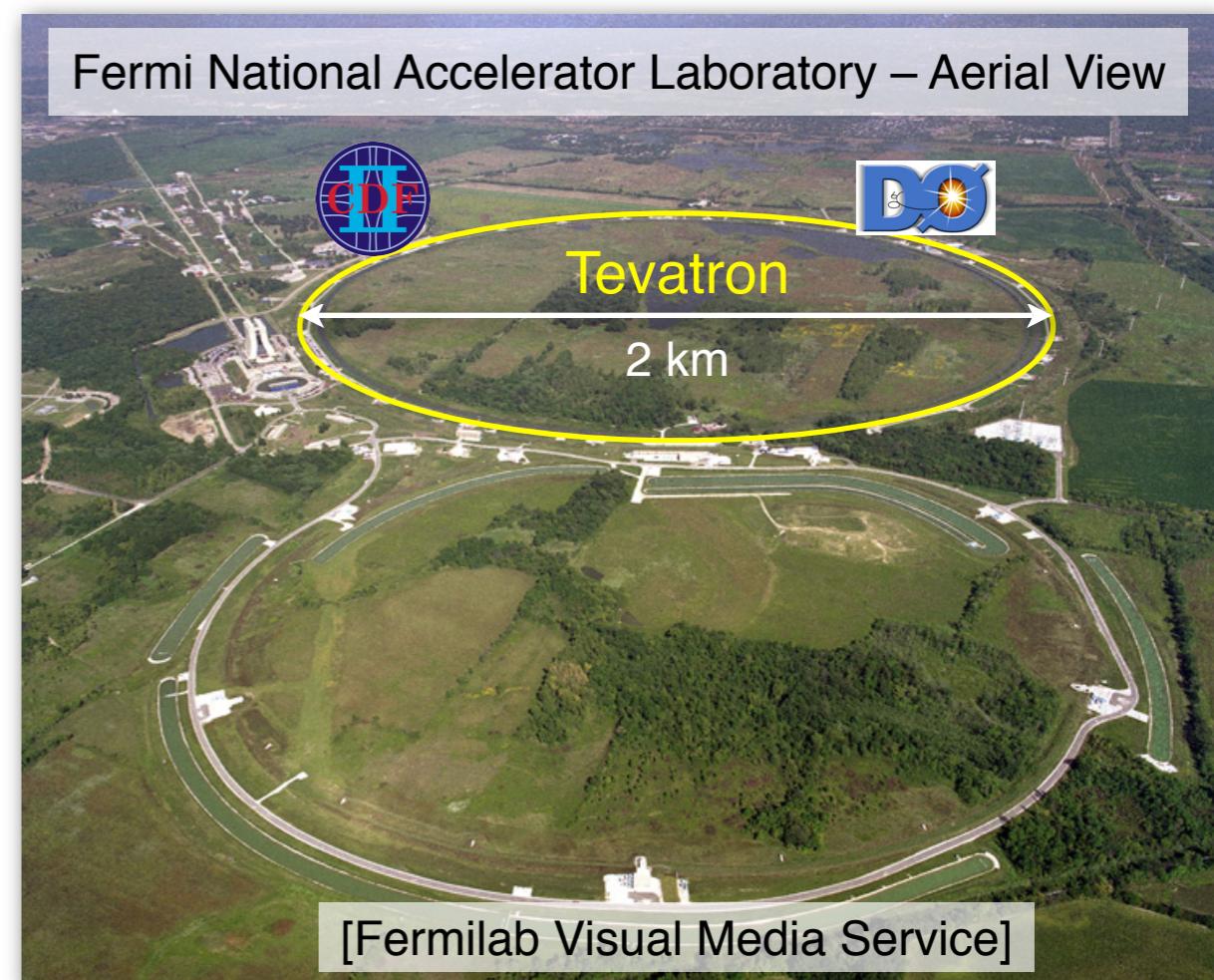
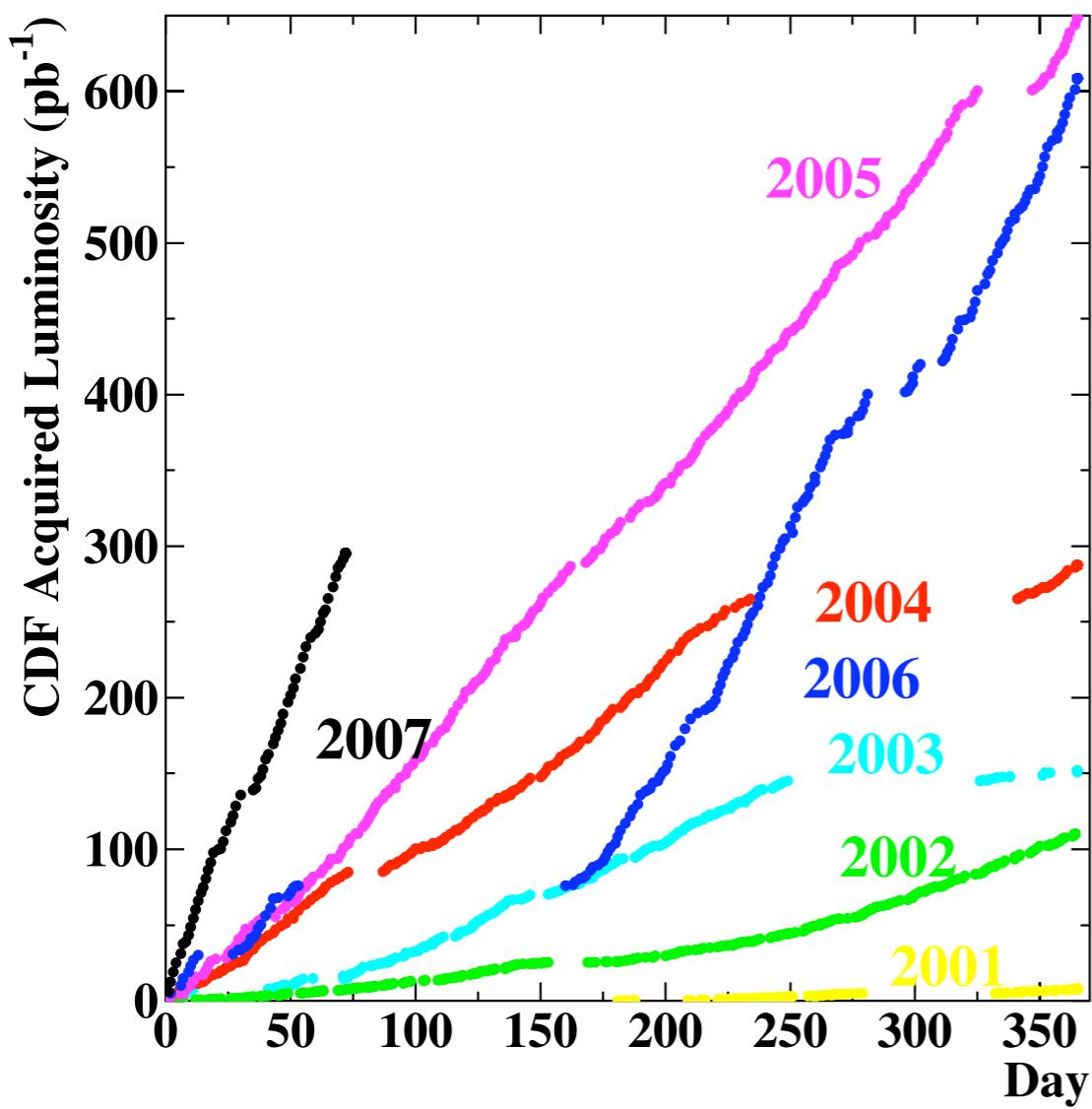


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Fermilab & The Tevatron



- Tevatron Run II (2001–2009):
 - Proton-antiproton collider: $\sqrt{s} = 1.96 \text{ TeV}$
 - 36×36 bunches
 - Record instantaneous peak luminosity:
 $292 \mu\text{b}^{-1} \text{ s}^{-1}$



- Experiments at the Tevatron:
 - Two multi-purpose experiments: CDF & DØ
 - More than 2.6 fb^{-1} delivered, more than 2.1 fb^{-1} recorded per experiment
 - Expect $6\text{--}8 \text{ fb}^{-1}$ by 2009



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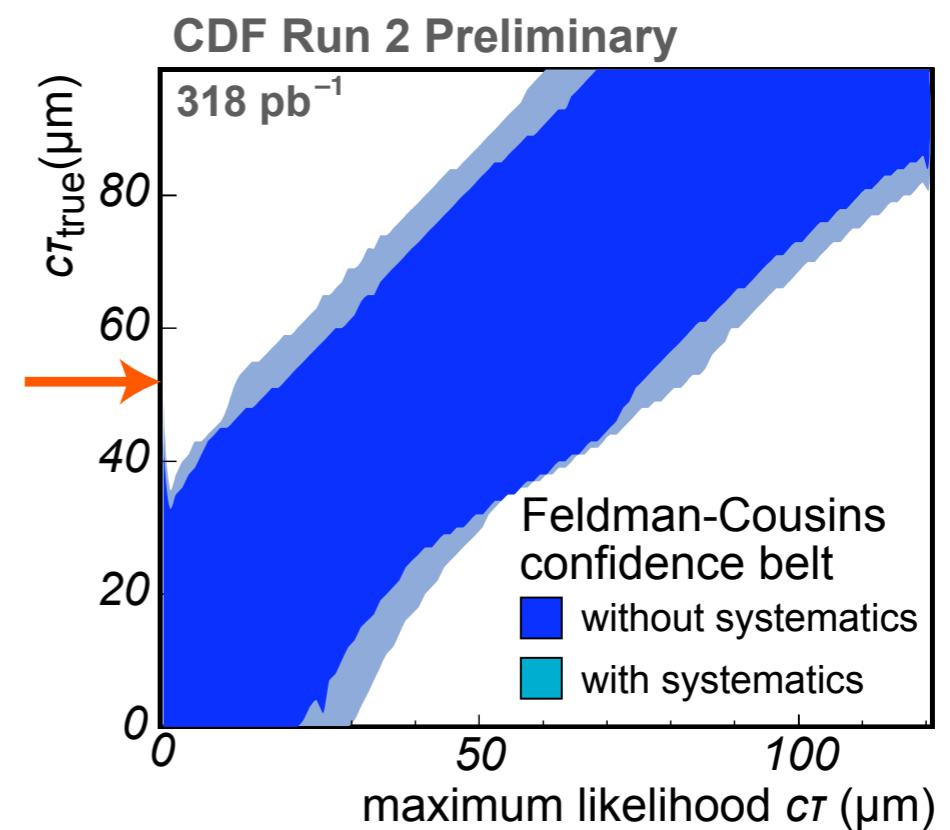
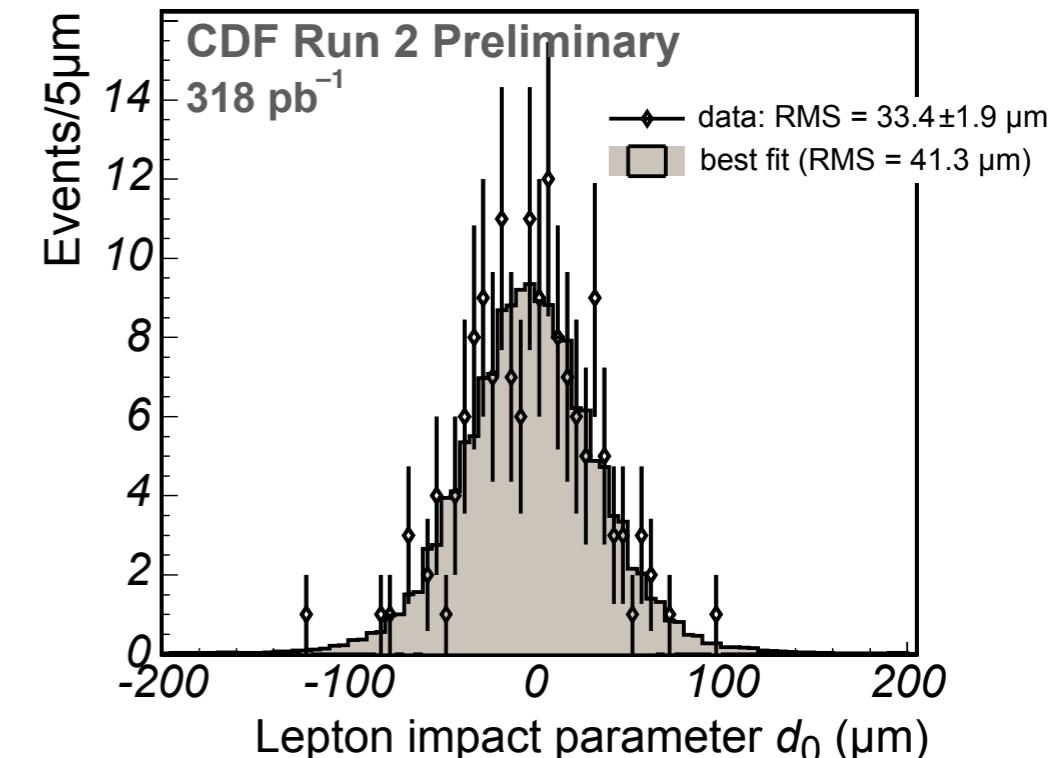
Top Lifetime



- Top lifetime in the Standard Model
 - Expected lifetime: $< 10^{-24}$ s
 - Constrained by unitarity of CKM matrix, but no direct measurements so far
- First direct measurement at CDF
 - 318 pb^{-1} , Lepton+Jets sample
 - Measure lepton impact parameter d_0
 - Calibrate impact parameter resolution in data with leptons from γ^*/Z decays
 - Create templates for signal & background
- Results:
 - Maximum likelihood: $c\tau = 0 \mu\text{m}$
 - Feldman-Cousins limit including systematics:

$$c\tau < 52.5 \mu\text{m} \quad (95\% \text{ C.L.})$$

[CDF Public Note 8104]





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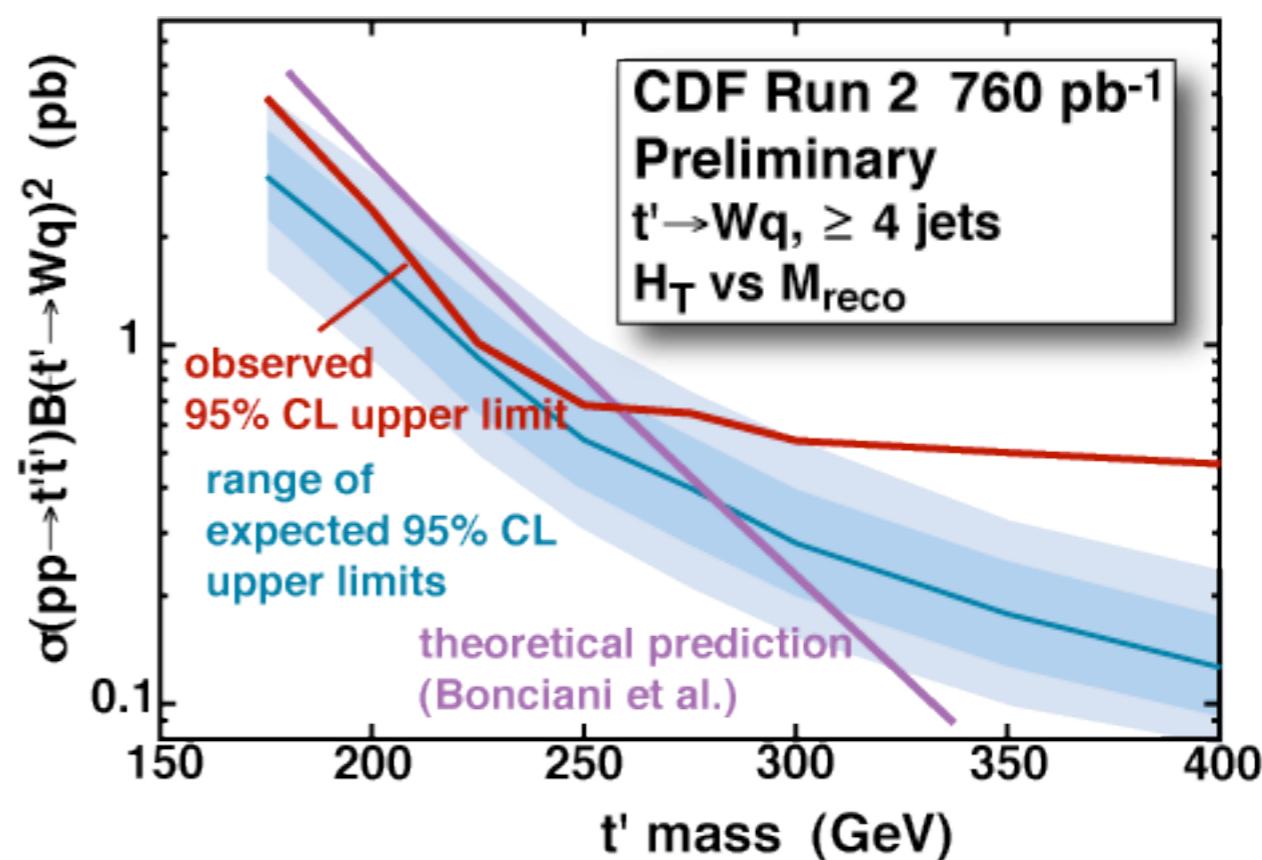
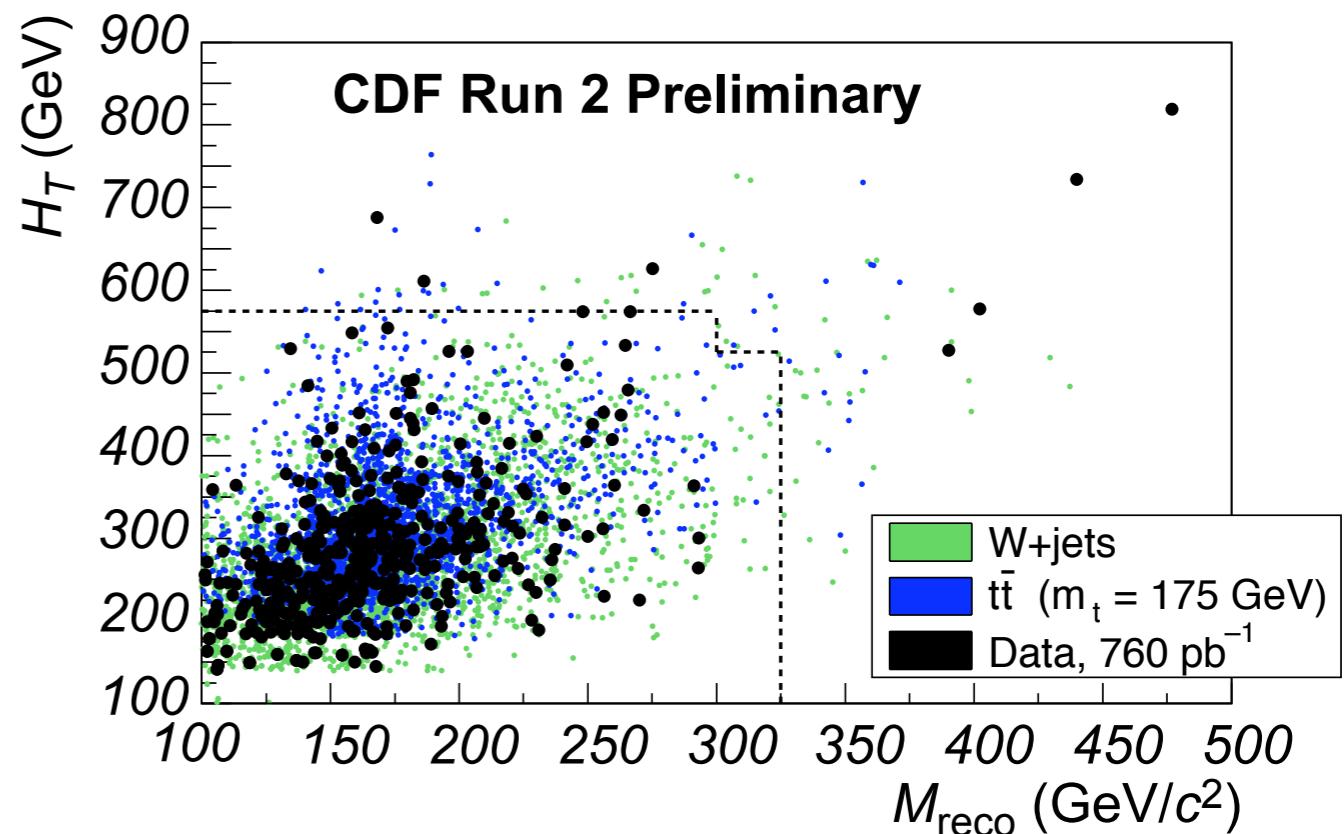
Search for a Massive t' Quark



- Model-independent search for decay $t' \rightarrow Wq$ ($t't'$ pair-produced)
 - 760 pb $^{-1}$ of Lepton+Jets data
 - H_T : sum of all lepton/jet transverse momenta and missing transverse energy
 - M_{reco} : reconstructed t' mass from kinematic fitter
- Mild excess** of 4 events with large (H_T, M_{reco}) : observed limit worse than expected limit

$m_{t'} > 258 \text{ GeV}/c^2$ (95% C.L.)

(expected: $m_{t'} < 290 \text{ GeV}/c^2$)





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Measurement of V_{tb}



- $|V_{tb}|$ constrained by unitarity of CKM matrix:
 $|V_{tb}| = 0.999$
- Tevatron: direct measurement of $|V_{tb}|$ from Top decays

$$R \equiv \frac{\text{BR}(t \rightarrow Wb)}{\text{BR}(t \rightarrow Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

- Idea: measure ratio R from relative rates of events with 0, 1, or 2 b-tags
- Challenge: efficiency to observe n b-tags
- CDF (162 pb $^{-1}$, Lepton+Jets & Dilepton datasets, Feldman-Cousins limit):

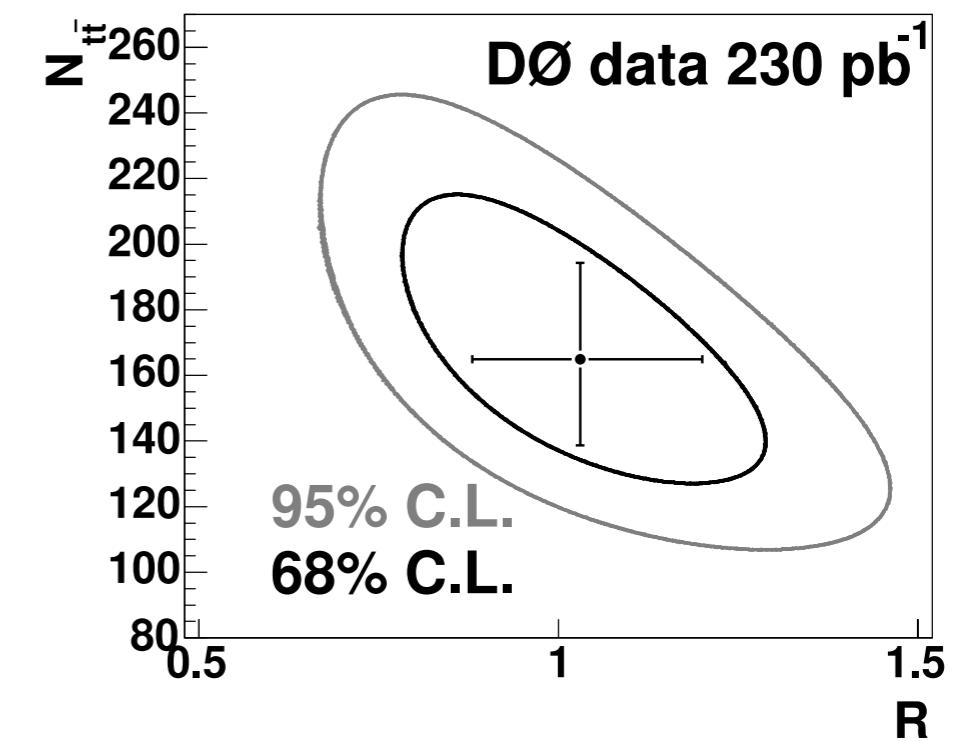
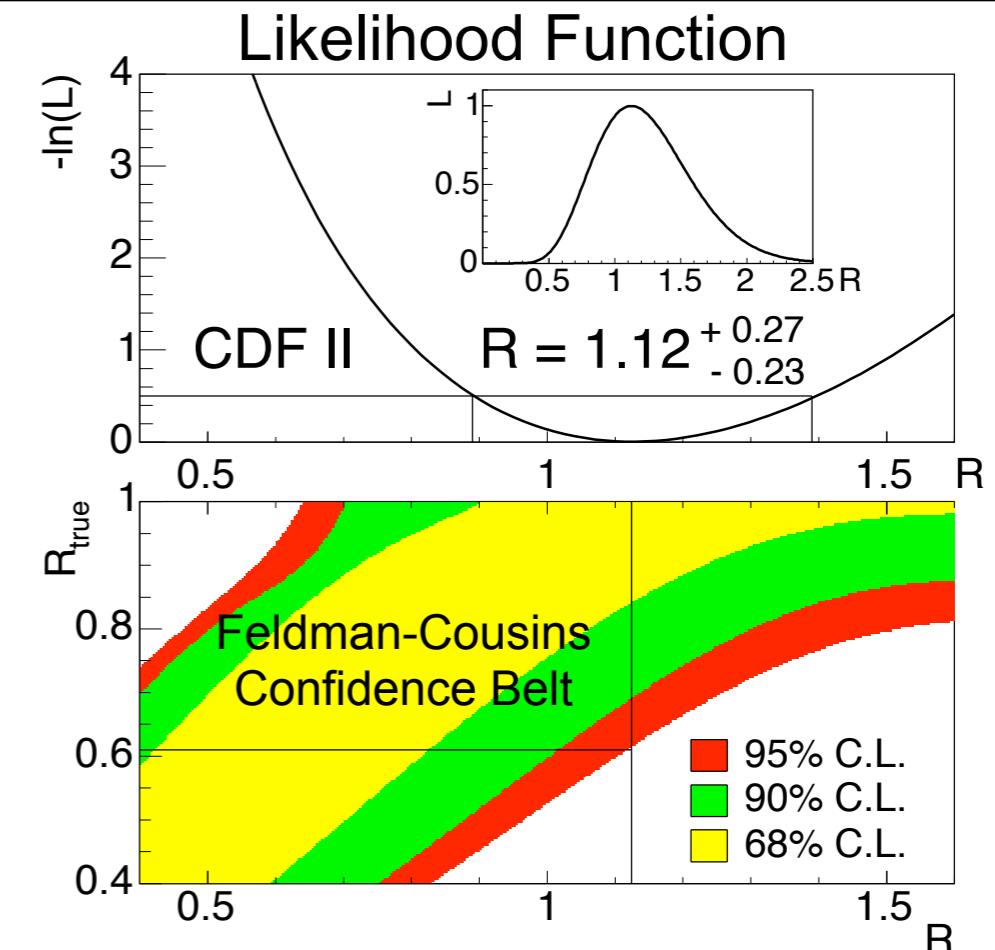
$$\begin{aligned} R > 0.61 & \quad (95\% \text{ C.L.}) \\ |V_{tb}| > 0.78 & \quad (95\% \text{ C.L.}) \end{aligned}$$

[D. Acosta *et al.*, Phys. Rev. Lett. **91** (2005) 102002]

- DØ (230 pb $^{-1}$, Lepton+Jets, Bayesian limit):

$$\begin{aligned} R > 0.61 & \quad (95\% \text{ C.L.}) \\ |V_{tb}| > 0.78 & \quad (95\% \text{ C.L.}) \end{aligned}$$

[V. M. Abazov *et al.*, Phys. Lett. **B639** (2006) 616]





Rencontres
de Moriond
1966

Kinematic Fitter



- Lepton + Jets signature:
 - High- p_T lepton
 - Missing transverse energy
 - 4 Jets (2 b-jets)
- Reconstruction of kinematics:
 - Constrain jet-jet mass to W mass
 - Constrain lepton-neutrino mass to W mass
 - Constrain W and b to Top masses
 - Jet assignment: 12 combinations per event (reduced if b-tagging information is used)
 - Unknown p_z of neutrino: 2 combinations
- Lowest χ^2 gives correct combination in 70% of the cases

$$\begin{aligned}\chi^2 = & \sum_{i=j,l} \frac{(p_T^i - \hat{p}_T^i)^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{\text{UE}} - \hat{p}_j^{\text{UE}})^2}{\sigma_j^2} \\ & + \frac{(m_{jj} - m_W)^2}{\Gamma_W^2} + \frac{(m_{\ell\nu} - m_W)^2}{\Gamma_W^2} \\ & + \frac{(m_{bjj} - m_t)^2}{\Gamma_t^2} + \frac{(m_{b\ell\nu} - m_t)^2}{\Gamma_t^2}\end{aligned}$$